OIL ANALYSIS BASICS

SECOND EDITION

REVISED AND UPDATED 2010

JIM FITCH AND DREW TROYER

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1. Lubrication Fundamentals

1.1 The Functions of a Lubricant

Lubricants come in fluid, grease and solid forms depending upon the requirements of the application. Lubricants can deliver some or all of the following benefits:

- **Friction and wear reduction** – By separating moving surfaces with a load-carrying fluid film, lubricants reduce friction. Friction generates heat and causes surface degradation in the form of wear (see Figure 1-1). Both heat and wear reduce the useful life of mechanical components and the lubricant itself. The degree to which component surfaces are separated, if at all, depends upon several factors, including load, speed and viscosity. Typically, in sliding contacts, the lubricant film provides 2 to 20 microns of component separation. Where fluid film separation can't be achieved, solid or chemical additives are often used to reduce friction and wear at frictional component surfaces.

- **Heat control** – Flowing lubricants absorb heat at the point at which it is generated so that it can naturally dissipate (by convection or thermal conductivity) or be transported to a heat exchanger or to the walls of the machine. Of course, when friction is reduced by a lubricant film, heat generation is reduced as well.

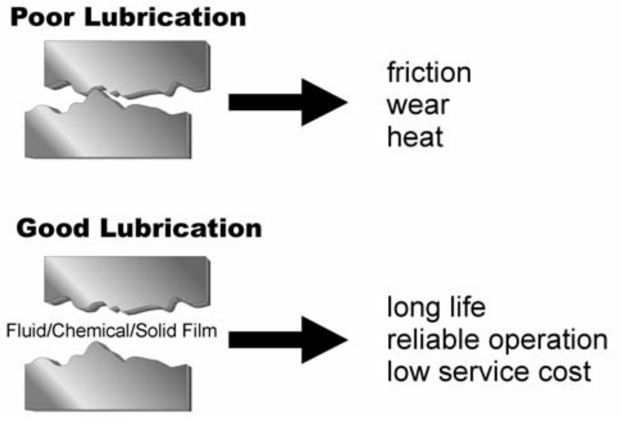


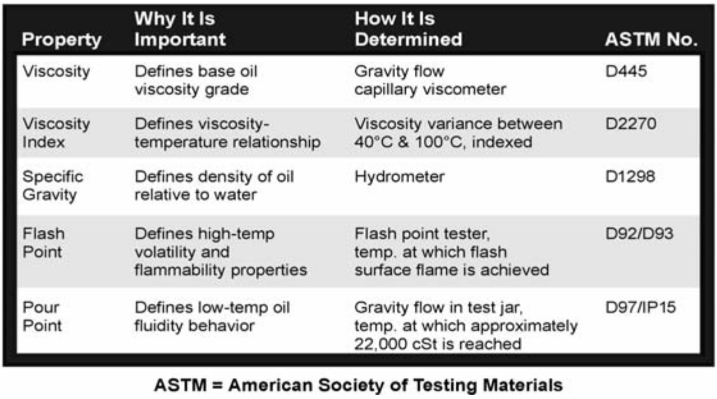
Figure 1-1 Oil Film Reduce Friction, Wear and Heat

- **Contamination control** – Lubricants such as grease can help seal the machine's components from the environment and, as such, stop or slow the ingress of contaminants like particles, water and chemicals to sensitive surfaces. Likewise, lubricating oils can pick up contaminants and carry them to a tank or sump, where they can settle by gravity, or to a filter (or separator), where they are removed.
- **Prevent chemical attack** – By coating component surfaces, lubricants can provide protection against rust and corrosion. Additives used in certain lubricants can neutralize the corrosive properties of acids that can develop over time.
- **Transfer of energy** – In hydraulic systems, the fluid is the relatively incompressible medium by which energy can be easily transmitted to produce force and motion in the actuation of cylinders, valves and hydraulic motors.

1.2 Base Stock Considerations

Lubricants can vary significantly from product to product. Figure 1-2 depicts some of the tests commonly used to describe physical properties of base oil – the foundational component in the formulation of a lubricant. Base oil provides most of the viscosity and serves as a host for the comingling of important chemical and solid additives. It determines

These Tests Help Describe Key Physical Properties of New Base Oils



Property	Why It Is Important	How It Is Determined	ASTM No.
Viscosity	Defines base oil viscosity grade	Gravity flow capillary viscometer	D445
Viscosity Index	Defines viscosity-temperature relationship	Viscosity variance between 40°C & 100°C, indexed	D2270
Specific Gravity	Defines density of oil relative to water	Hydrometer	D1298
Flash Point	Defines high-temp volatility and flammability properties	Flash point tester, temp. at which flash surface flame is achieved	D92/D93
Pour Point	Defines low-temp oil fluidity behavior	Gravity flow in test jar, temp. at which approximately 22,000 cSt is reached	D97/IP15

ASTM = American Society of Testing Materials

Figure 1-2 Common Physical Properties of Lubricant Base Oils

many of the operating performance properties of the resultant fluid lubricant or grease. Most base oils are mineral oils, meaning they are produced from crude oil (petroleum) using a number of different refining processes. Usually, refining begins with fractional distillation, whereby the molecules are sorted according to size (weight) and type by varying temperature and pressure (vacuum). Then, other refining processes might be applied to enhance the end result, including:

- **Solvent extraction** – The distilled oil is mixed with solvents in which undesirable aromatic molecules dissolve, enabling their separation from the oil's other molecules.
- **Hydrogen processing** – This includes:
    - Mild hydrotreating – Low-temperature/low-pressure hydrotreating removes sulfur, oxygen and nitrogen compounds, but does not necessarily affect aromatics.
    - Severe hydrotreating – High-temperature/high-pressure hydrotreating is used to saturate oxidation-prone aromatic molecules. This converts them into more stable naphthenes and paraffins and also removes most polar (oxygen-containing) compounds.
- **Acid refining** – Unsaturated compounds are extracted using sulfuric acid, leaving an acid sludge that is then removed and neutralized.
- **Clay refining** – Using special clay materials, many highly reactive unsaturated molecules can be removed.
- **Solvent or catalytic dewaxing** – After solvent refining, waxes are removed from paraffinic oil using solvents, or they are converted into shorter chain hydrocarbons using special catalysts.

Mineral-based lubricating oils are combinations of millions of different hydrocarbon molecules. Generally, lubricating base oils are produced from paraffinic crude stock. Occasionally, naphthenic oils are used for certain specialty applications, especially where low-temperature fluidity is important. Select properties of the two base oils are compared in Figure 1-3. Aromatic oil also is presented for comparison purposes, but it is not generally recommended in the formulation of lubricating oils.

Property Method	ASTM	Paraffinic Oil	Naphthenic Oil	Aromatic Oil
Viscosity (cSt) @ 40°C	D445	40	40	36
Viscosity (cSt) @ 100°C	D445	6.2	5	4
Viscosity Index	D2270	100	0	-185
Specific Gravity	D287	0.8628	0.9194	.9826
Flash Point °C	D92	229	174	160
Pour Point °C	D97	-15	-30	-24
% Paraffinic	D3238	66%	45%	23%
% Napthenic	D3238	32%	41%	36%
% Aromatic	D3238	2%	14%	41%

Figure 1-3 Comparison of Typical Base Oil Properties (Ref. No. 1)

Mineral vs. Synthetic Base Oils

A minority of the lubricants in service are formulated using synthetic base oils instead of base oils refined from crude. The molecules of synthetic base oils are either entirely man-made (by synthesis or polymerization) or are highly modified by the application of pressure, temperature and/or catalysis. There are many different types of synthetic oils with varying properties. What follows are a few potential benefits associated with using a synthetic base oil (note, not all benefits apply to all synthetics):

- Increased oxidation stability
- Improved lubricity
- Fire resistance
- Better thermal resistance
- Extended drain intervals
- Better low-temperature fluidity
- Lower volatility and higher flash point
- Natural detergency
- Higher viscosity index

These benefits must be compared to the possible limiting factors associated with the use of synthetic lubricants to determine feasibility and risk. These factors might include:

- High purchase cost

- Seal and material incompatibility
- Potential toxicity (some synthetics only)
- High disposal cost (some synthetics only)
- Possible incompatibility with mineral oil
- Poor hydrolytic stability (chemical degrades in the presence of water)
- Poor additive solubility (some synthetics are not mixable with additives)
- Poor lubricity (some synthetics only)

The American Petroleum Institute (API) has created standard categories for base oil used in the formulation of lubricants. There are five categories called groups. The differences between the API base oil categories are shown in the table in Figure 1-4.

These different groups are used to quickly characterize the quality of a base oil with respect to typical needs of formulated lubricants. For instance, Group I base oils have the highest sulfur content, have the lowest level of saturates and the lowest viscosity index. These are less desirable properties and are generally avoided in most premium lubricant formulations. Conversely, Group II through Group IV base oils generally have more favorable properties compared to Group I in these same performance areas. However, it is worth noting that there are some properties such as additive solubility where Group I base oils outperform Groups II to IV; as such, many lubricant formulations using Group I base oils are very successful in the target applications. This is in part due to the additive system that is selected.

API Base Oil Categories

Base Oil Category	Sulfur (%)		Saturates %	2007 Global Base Stock Distribution	Viscosity Index
Group I	>0.03	and/or	<90	66%	80 to 120
Group II	<0.03	and	>90	20%	80 to 120
Group III	<0.03	and	>90	5%	>120
Group IV	PAO synthetic base oils				
Group V	All other base oils not included in Groups I, II, III or IV				

Figure 1-4 API Groups for Categorizing Base Oils According to Key Physical and Chemical Properties

1.3 Lubrication Fundamentals

Ideally, the machine's component surfaces are physically separated by a film of lubricant. In the absence of surface-to-surface contact, and assuming the oil is free of contamination (discussed later), the machine should operate with little friction and produce little to no wear. However, when surface-to-surface contact is likely, friction at the boundary must be reduced using other means. In the paragraphs that follow, different primary lubrication regimes are summarized and discussed:

- **Hydrodynamic lubrication** – Called full-film lubrication, hydrodynamic lubrication is the separation of components by a "wedge" of oil that is produced hydrodynamically (see Figure 1-5). This occurs when two surfaces slide during relative motion. Common locations where sliding and hydrodynamic lubrication occurs are in journal bearings (sleeve bearing) and tilting-pad thrust bearings.

  The formation of a hydrodynamic film depends upon the machine's surface geometry, speed, load and the oil's viscosity. Speed and viscosity are inversely related to load in the formation of hydrodynamic lubrication and film thickness. In other words, increasing

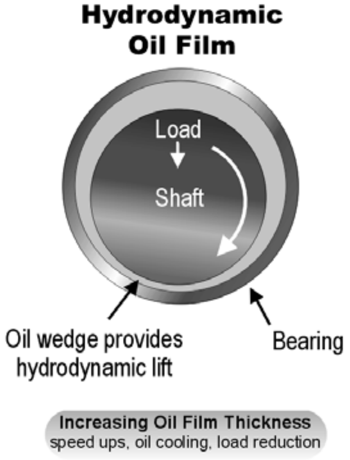


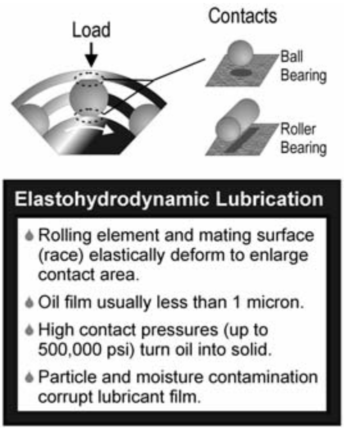
Figure 1-5 Rotating Shaft in a Journal Bearing Produces an Oil Wedge to Separate Sliding Surfaces – Hydrodynamic Lubrication

speed and/or viscosity, or decreasing load, will decrease the time it takes to achieve hydrodynamic separation and increase the film's thickness. Likewise, the component surface geometry, surface area and surface smoothness affect the ease with which the hydrodynamic film is established. Hydrodynamic lubrication is not achieved during startup and, likewise, is lost during shutdown. Sudden speed and/or load variations (shock loads) impair hydrodynamic lubrication. Occasionally during machine startup, an attempt to produce a hydrostatic film using pumps to "jack" the shaft up on the bearing are used to speed development of the hydrodynamic film and reduce related wear.

- **Elastohydrodynamic (EHD) lubrication** – EHD lubrication is formed in rolling contacts where surfaces converge upon a point or a line, as in a rolling element bearing or the pitch line of two meshing gear teeth. Under point or line contact conditions, little surface area is available in the mating load zone. However, due to bearing material elasticity, during operation, bearing metal actually deforms to produce the small load-bearing area under which a hydrodynamic film is formed.

  Because the formation of the hydrodynamic film depends upon the deformation of the component's surface, the lubrication regime is called elastohydrodynamic lubrication (see Figure 1-6). The EHD oil film that separates component surfaces is very small, often less than 1 micrometer in thickness. Because a majority of the component's load is momentarily transferred across a very small area, pressure in this area is very high, as much as 500,000 pounds per square inch (psi).

  During the period of high transient pressure, the oil momentarily changes from a liquid to a solid. The ability of a lubricant to achieve this important transformation is called its pressure-viscosity coefficient. Once the pressure is released, the lubricant returns to the previous liquid state unharmed. The extreme localized pressures where rolling contacts occur increases the importance of effective lubrication. Unlike hydrodynamic lubrication, which creates an oil film under sliding conditions, EHD lubrication works during rolling contact.



Elastohydrodynamic Lubrication

- Rolling element and mating surface (race) elastically deform to enlarge contact area.
- Oil film usually less than 1 micron.
- High contact pressures (up to 500,000 psi) turn oil into solid.
- Particle and moisture contamination corrupt lubricant film.

Figure 1-6 Elastohydrodynamic Lubrication Occurs in Rolling Contacts

- **Boundary lubrication** – Where mechanical surface separation from hydrodynamic or EHD lubrication can't be achieved, friction and wear control depend upon other characteristics of the lubricant. This condition is called boundary lubrication. Boundary lubrication prevails under the following conditions:
    - Oil film thickness does not exceed the component's surface roughness.
    - Equipment is subjected to frequent starts and stops, shock-load conditions, high static loads or slow speeds.
    - Operational requirements dictate the use of low-viscosity oil, compromising friction and wear control of some system components.

  Lubrication under boundary conditions may require the use of soft metals that generate less friction under contact, additives that produce a chemical reaction on the surface of the components producing low-friction contact (discussed later), or solid lubricants (i.e. microscopic particles of graphite or molybdenum disulfide) to reduce friction and manage wear.

  Adhesive wear (scuffing) and abrasive wear (two-body) often occur unless additives are used to achieve chemical film strength under boundary lubrication. The types of additives that provide this type of protection are extreme-pressure (EP) additives and anti-wear additives. These additives are needed in many gearbox applications, engines and hydraulic systems where boundary lubrication conditions are expected.

- **Mixed-film lubrication** – This is a term that is commonly used to describe the transition between boundary lubrication and either hydrodynamic lubrication or EHD lubrication. In such an instance, both the base oil viscosity and the additives are working in unison to reduce friction and wear.

1.4 Additives and their Functions

Additives are chemicals introduced to the base oil to alter or add one or more performance properties. In general, it can be said that additives are used to:

- Enhance existing base oil properties
- Suppress undesirable base oil properties
- Impart new properties to base oils

What follows is a review of common oil additives and their functions.

Antioxidants/oxidation inhibitors – Lubricating oil can react with oxygen, especially at high temperatures, to begin the process of permanent degradation and risk harm to the machinery. This reaction forms undesirable by-products, including hydroperoxides, free radicals, ketones, aldehydes and organic acids. The rate of this process, called oxidation, is dependent upon the following factors:

- Aeration (affects the amount of oxygen available to react with oil molecules)
- Temperature (the rate of oxidation approximately doubles when the temperature increases by 10 degrees Celsius)
- Water (causes hydrolysis and promotes oxidation)
- Metal catalysts (copper, lead, iron and other chemically active metals promote oxidation of the oil; wear debris is the most prominent source of these catalysts)

Oxidative reactions change the oil's chemical and physical properties in the following ways:

- Viscosity increases
- More acidity (corrosion potential)
- Specific gravity increases
- Oil color is darker
- Varnish and deposits form on component surfaces
- Sludge forms

Antioxidant/oxidation-inhibiting additives help combat the oxidation process and prolong the life of the oil. Primary antioxidant additives scavenge pro-oxidants such as free radicals, producing less-dangerous by-products. Secondary antioxidants decompose hydro-peroxides. A third type of antioxidant is a metal deactivator which mitigates the effects metal catalysts have on oxidation. Antioxidant additives sacrifice themselves to protect the oil and extend its useful life (see Figure 1-7). The following are common antioxidant/oxidation-inhibiting additives:

- Hindered phenols – primary
- Aromatic amines – primary
- Zinc dithiophospates (also provides anti-wear protection) – secondary
- Metal sulfonates and phenates – metal deactivators

Rust Inhibitors – Water adversely affects both lubricants and machine surfaces. Rust is caused by water contamination and is a common form of corrosive wear that reduces the useful life of iron and steel

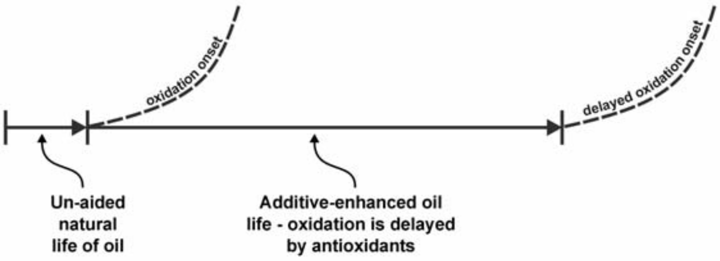

oxidation onset
delayed oxidation onset
Un-aided natural life of oil
Additive-enhanced oil life - oxidation is delayed by antioxidants

Figure 1-7 The Onset of Oxidation Cannot Be Prevented, Only Delayed, by Antioxidants

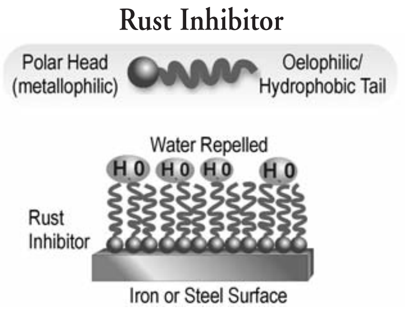


Figure 1-8 Rust Inhibitors Forms a Barrier Film to Repel Water

machine components, forming hard oxide particles and pitted machine surfaces. To protect against rust, many oils are formulated with rust inhibitors. As Figure 1-8 depicts, rust inhibitors are polar molecules that are chemically attracted to steel or iron surfaces (metallophilic) and have an oil-soluble (oleophilic) tail. The additive forms a hydrophobic barrier film to repel water from the iron or steel surfaces. By separating the water from the component surface, the rusting process is inhibited. The following are typical rust-inhibiting additives:

- Sulfonates
- Phosphates
- Organic acids, succinimides, esters and amines

Most rust inhibitors are alkyl succinic acids. An alkyl is a long-chain molecule that provides oil solubility and water repellency properties.

Dispersants and Detergents – Dispersants are polar molecules that envelope soot particles formed as a by-product of fuel combustion in engines. As such, they are primarily used in engine oil formulations. The additive is designed to inhibit soot agglomeration and later deposition onto component surfaces, especially in cooler zones of the engines (oil pan, rocker cover, etc.). The dispersant helps keep soot particles small and finely divided so that they remain suspended and don't condense easily onto component surfaces (see Figure 1-9). Agglomerated soot (from poor dispersancy) also can lead to harmful deposits underneath piston rings interfering with flexing and movement of these rings within their grooves (causing excess wear or ring breakage). Too much soot from overextended oil drain intervals can overwhelm the oil's ability to maintain suitable dispersancy. Water and coolant contamination also can disrupt dispersancy.

Detergents help cleanse high-temperature surfaces (pistons, rings, valves, etc.) from hard deposits that form from combustion by-products and oil oxidation. They rarely are used in applications other than engine oil formulations. Additionally, they provide an over-base feature to neutralize the acids that are generated from combustion, contamination and oil oxidation (see Figure 1-10). This over-base feature (or alkalinity) is what gives engine oils their base number (BN), which is a common property monitored in oil analysis (discussed later). Without neutralization of common acids such as carboxylic acids, formic acids, glycolic acids, sulfuric acids and nitric acids, damage to

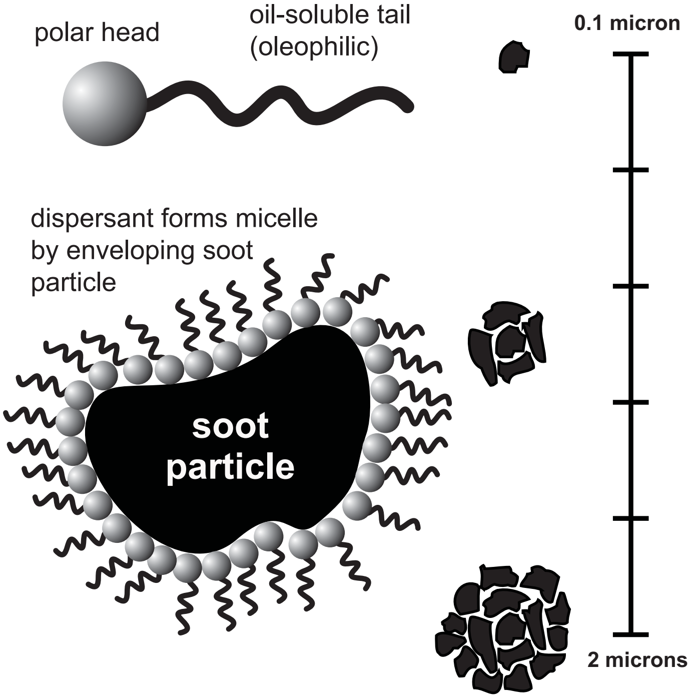

polar head
oil-soluble tail (oleophilic)
0.1 micron
dispersant forms micelle by enveloping soot particle
soot particle
2 microns

Figure 1-9 Dispersants are Used Primarily in Engine Oil to Control Agglomeration of Soot Particles

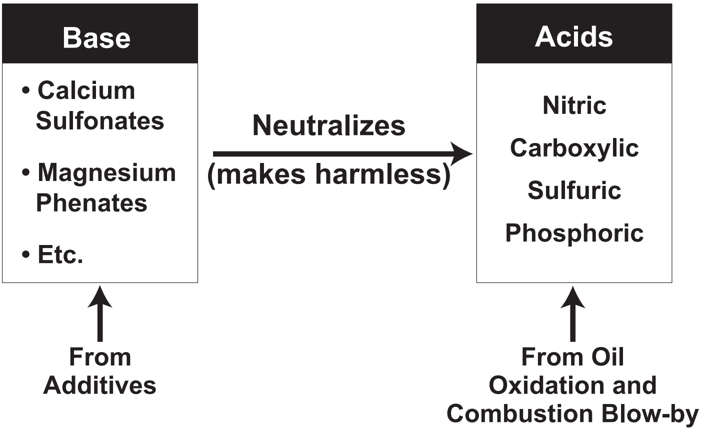


Figure 1-10 Detergents and other Over-based Additives Neutralize Acids from Oil Oxidation and Combustion Blow-by

internal surfaces will occur from corrosion. Most detergent-additive compounds are organo-metallic soaps of barium, calcium and magnesium and include:

- Calcium sulfonate
- Barium sulfonate
- Magnesium sulfonate
- Calcium phenate

Anti-wear and Extreme-pressure Additives – Anti-wear (AW) and extreme-pressure (EP) additives protect lubricated components from excessive friction and wear under the boundary conditions as previously described. EP additives are also known as anti-scuff additives. Under high pressure, these chemically active additives react with component surfaces to form soft, soap-like oxide films that offer enhanced lubricity at the frictional boundary contacts between sliding surfaces (see Figure 1-11). AW and EP additives differ in the depth to which they react with component surfaces (see Figure 1-12) and the protection they provide.

It is ideal to avoid boundary lubrication conditions. When it can't be avoided, it is best to choose the weakest (least chemically active) additive that will accomplish the task of friction control to avoid unnecessary heat and surface degradation. Stronger additives, such as sulfur-phosphorous EP additives, should only be used as required and usually only when high loads, shock loads and/or high-contact rubbing temperature conditions exist. Common AW and EP additives include:

- Zinc dithiophosphate/dialkyl dithiophosphate (ZDDP) (AW)
- Tri-cresyl phosphate (TCP) (AW)
- Sulfur-phosphorous (S-P) (EP)
- Soluble molybdenum disulfide (EP)

It is sometimes advisable to use solid lubricants such as molybdenum disulfide, graphite and PTFE as additives to provide further protection against two-body abrasion and scuffing. However, these additives present the risk of settling and removal by filtration. Therefore, they are more commonly used in grease formulations.

VI Improvers – VI improvers are long-chain polymers of high molecular weight used to boost the viscosity index (VI) of lubricants that are routinely exposed to wide-ranging oil temperatures. An oil's temperature, whether high or low, directly impacts its viscosity. Low temperatures increase viscosity, while high temperature decreases viscosity. Both viscosity extremes (low and high) can degrade the quality of lubrication. VI improvers are used in oil formulations to reduce the rate of viscosity change as oil temperatures vary during service.

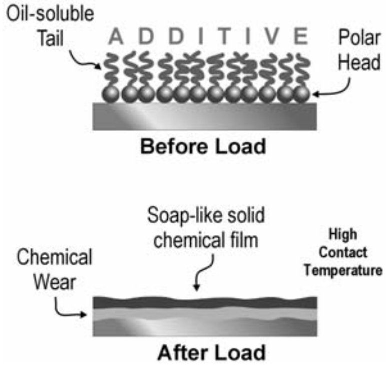
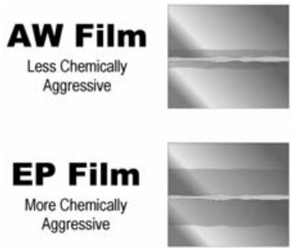


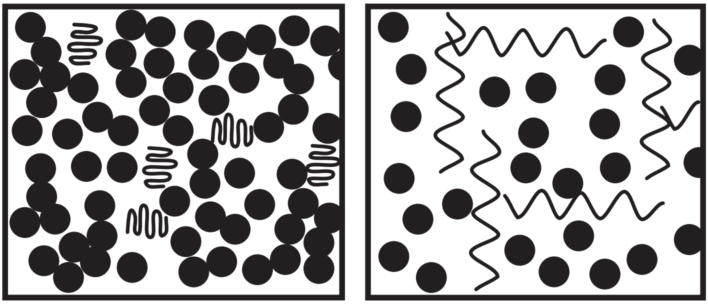
Figure 1-11



AW and EP Additives Reduce Wear Under Boundary Conditions

Figure 1-12

Additives: Viscosity Index (VI) Improvers (Modifiers)



Low Temperature High Temperature

Figure 1-13 VI Improvers Change in Apparent Size with Change in Temperature

VI improver molecules do this by shrinking (becoming smaller) as oil temperature drops and unfurling (becoming larger) as oil temperature rises (see Figure 1-13).

VI improvers consist primarily of polymers and esters such as the following:

- Olefin copolymer (OCP)
- Polyacrylate
- Polymethacrylate ester (PMA)
- Polyisobutylene (PIB)

VI improvers can be found in most engine oils, hydraulic fluids, automatic transmission fluids and gear lubricants.

Foam Inhibitors or Defoamants – Defoamants inhibit the formation of stable foams above the oil level in tanks, reservoirs and sumps. Defoamants are typically polymers such as methyl silicone or polymethacrylate. They are dispensed as micro-globules in the oil, around 10 microns in size. These globules are pulled up as the air rises and then weaken the bubbles that form, causing them to burst.

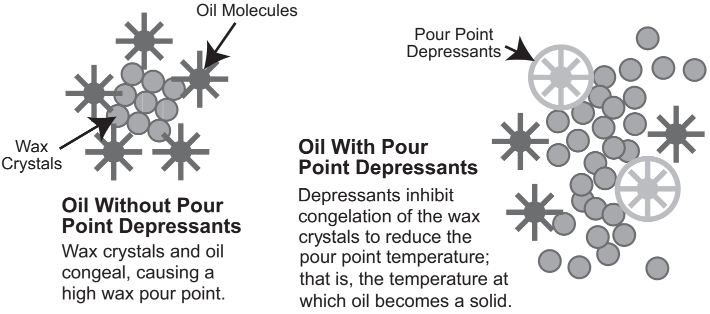

Oil Molecules
Wax Crystals
Oil Without Pour Point Depressants
Wax crystals and oil congeal, causing a high wax pour point.
Pour Point Depressants
Oil With Pour Point Depressants
Depressants inhibit congelation of the wax crystals to reduce the pour point temperature; that is, the temperature at which oil becomes a solid.

Figure 1-14 Pour Point Depressant Additives Help Lower the Pour Point of Paraffinic Base Oils

Pour Point Depressants – Pour point depressants (PPD) are polymers that allow oil and lubricants to flow at very low wintertime temperatures without heavy wax formation and viscous thickening. PPDs interfere with wax formation at these cold temperatures and enable the oil to remain pumpable (flowable) (see Figure 1-14). Pour point depressants are typically used in paraffinic base oils in applications where extreme low machine startup temperature conditions are possible. Most paraffinic motor oils employ the use of pour point depressants.

References:

1. Society of Tribologists and Lubrication Engineers. “Starting from Scratch Tribology Basics”, Lubrication Engineering

2. Oil Analysis and Condition-Based Maintenance

While the benefits of detecting abnormal machine wear or an aging lubricant condition are important and frequently achieved, they should be regarded as low on the scale of importance compared to the more rewarding objective of failure avoidance (see Figure 2-1).

Whenever a proactive maintenance strategy is applied, three steps are necessary to insure that its benefits are achieved (see Figure 2-2). Since proactive maintenance, by definition, involves continuous monitoring and controlling of machine failure root causes, the first step is to set a target, or standard, associated with each root cause. In oil analysis, root causes of greatest importance relate to fluid contamination (particles, moisture, heat, coolant, etc.), wrong oil and additive degradation.

However, the process of defining precise and challenging targets (e.g., high cleanliness) is only the first step. Control of the fluid's conditions within these targets must then be achieved and sustained. This is the second step toward proactive maintenance and often includes an audit of how fluids become contaminated and then systematically eliminating these entry points. Often, upgrading filtration and the use of separators are required to meet proactive maintenance objectives.

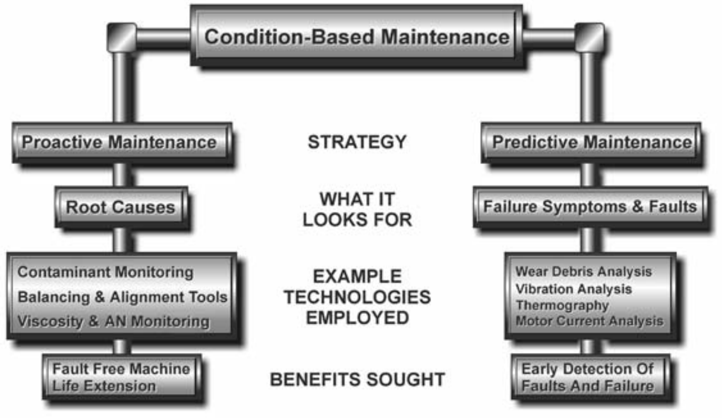

Condition-Based Maintenance
Proactive Maintenance
STRATEGY
Predictive Maintenance
Root Causes
WHAT IT LOOKS FOR
Failure Symptoms & Faults
Contaminant Monitoring
Balancing & Alignment Tools
Viscosity & AN Monitoring
EXAMPLE TECHNOLOGIES EMPLOYED
Wear Debris Analysis
Vibration Analysis
Thermography
Motor Current Analysis
Fault Free Machine Life Extension
BENEFITS SOUGHT
Early Detection Of Faults And Failure

Figure 2-1 Condition-based Maintenance is the Combination of Proactive Maintenance and Predictive Maintenance

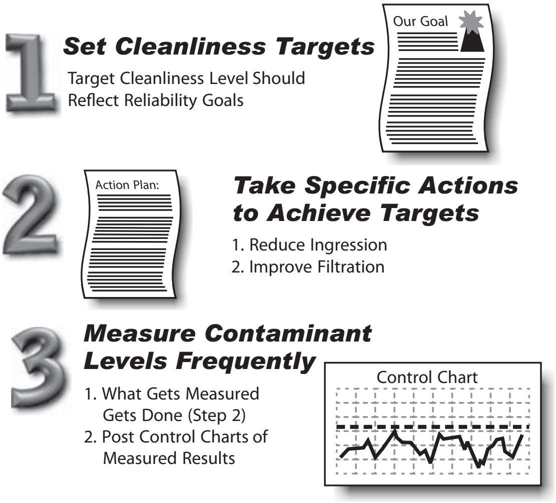

1
Set Cleanliness Targets
Target Cleanliness Level Should Reflect Reliability Goals
Our Goal
2
Action Plan:
Take Specific Actions to Achieve Targets
1. Reduce Ingression
2. Improve Filtration
3
Measure Contaminant Levels Frequently
1. What Gets Measured Gets Done (Step 2)
2. Post Control Charts of Measured Results
Control Chart

Figure 2-2 Deployment of Proactive Maintenance Involves Three Steps

The third step is the vital action element of providing the feedback loop of an oil analysis program. When exceptions occur (e.g., over-target results), remedial actions then can be immediately commissioned. Using the proactive maintenance strategy, contamination control becomes a disciplined activity of monitoring and controlling high fluid cleanliness, not a crude activity of trending dirt levels.

When the life-extension benefits of proactive maintenance are flanked by the early warning benefits of predictive maintenance, a comprehensive condition-based maintenance program results. While proactive maintenance stresses root cause control, predictive maintenance targets the detection of incipient failure of both the fluid's properties and machine components like bearings and gears. It is this unique, early detection of machine faults and abnormal wear that is frequently referred to as the exclusive domain of oil analysis in the maintenance field.

2.1 Reliability-Centered Maintenance (RCM)

RCM is the systematic process with which to optimize reliability and associated maintenance tactics with respect to operational requirements. Economic optimization of machine reliability relative to organizational goals is the primary objective of the RCM process. Simply stated, RCM helps us ensure that if we spend a dollar on improving reliability, we are getting the full dollar back, plus some acceptable return on the investment.

The process by which a reliability strategy is selected according to RCM is very systematic and logical (see Figure 2-3). As the flow diagram suggests, assets are audited with respect to their role in overall system reliability and productivity. If acceptable, no changes are required. If unacceptable, then questions about the criticality of the asset define the need to identify the most efficient means of attaining the necessary reliability. If the asset is deemed non-critical, for example, it is simply run to failure and then rebuilt or replaced. For mission-critical systems, advanced maintenance techniques are typically the first choice because their use is relatively inexpensive compared to redesign and the employment of redundancy.

In some cases, redesign or employment of redundancies is required to meet the objectives of the organization. Redesign in the form of proactive measures to control (and monitor) lubricant contamination, alignment, balance, etc., is usually much less expensive to deploy than failure-detection strategies. Conversely, more involved system redesign is usually very expensive and often produces unpredictable results. The employment of redundant systems is the most expensive method to improve reliability, but it provides very sure results. Employment of RCM helps to avoid the casual application of the latest “panacea” strategy, avoiding mistakes that waste resources and provide mediocre and unpredictable performance.

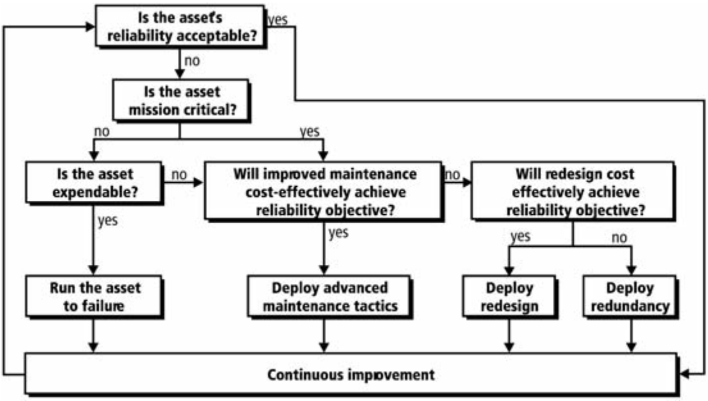

Is the asset's reliability acceptable?
yes
no
Is the asset mission critical?
no
yes
Is the asset expendable?
no
Will improved maintenance cost-effectively achieve reliability objective?
no
Will redesign cost effectively achieve reliability objective?
yes
yes
yes
no
Run the asset to failure
Deploy advanced maintenance tactics
Deploy redesign
Deploy redundancy
Continuous improvement

Figure 2-3 Decision Tree for RCM

3. Contamination Control

Contamination wreaks havoc in various ways on hydraulic and lubricated mechanical systems. It enters from the atmosphere or is generated from within to rob lubricants and components of precious life. Contamination, by definition, is anything in the oil that is foreign to the oil and machine. The four most common and destructive lubricant contaminants are discussed below.

3.1 Particle Contamination

Particles are responsible for much of the wear that leads to mechanical failure. The amount of damage inflicted by particles depends largely upon their population, size, shape, hardness and chemistry. Particles must be controlled in any system deemed critical to operation or expensive to repair. What follows is a concise summary of the four ways that particles can rob precious productivity and profits:

1. **Surface Removal.** This is the product of three-body abrasion in sliding contact zones and surface-fatigue in rolling contacts. Under sliding conditions, clearance-sized particles enter the oil film between surfaces and cut away material much like a lathe cuts metal (see Figure 3-1). This is referred to as three-body abrasion, where the particle becomes the third body. Under rolling contact conditions, particles transfer concentrated load between two surfaces in relative motion, resulting in surface fatigue, dents, pits and spalling (see Figure 3-2). Particle-contaminated oil traveling at high velocity also can cause wear known as particle-impingement erosion.

   Machines exposed to dense terrain dust from ambient air are the highest risk. These particles are harder than internal frictional surfaces, causing plowing, cutting and pitting. Machine components can only tolerate so much material loss. For instance, a 20-gallon-per-minute (gpm) hydraulic gear pump will have lost more than 30% of its volumetric efficiency when just 10 grams of wear metal have been generated.

2. **Restriction of Oil Flow and Part Movement**. Particles can form deposits, impede part movement and starve systems of oil. While no or limited wear may have occurred, this too can contribute to business interruption and expensive repairs. The most notorious example of this type of failure is silt-lock of electro-hydraulic valves. These valves can become jammed due to particles lodged between the spool and bore.
3. **Increased Consumption of Lubricants and Filters.** The ways in which particles can shorten lubricant service life and impair its performance are numerous. Particles accelerate additive depletion, leading to premature oil oxidation, oil-water emulsion problems, impaired corrosion protection and poor film strength. The result is higher fluid consumption and distress to the machine. Likewise, undeterred particle ingression will lead to wastefully high filter consumption.
4. **Higher Energy Consumption and Environmental Impact.** There are many ways that particles increase mechanical friction, impair anti-friction additive performance and decrease operating efficiencies in machinery. The more energy and fuel consumed due to these losses, the more waste stream that pollutes the atmosphere.

Contaminant Exclusion

For many machines, the exclusion of contamination is the only practical way to control contamination. This is because these machines either have no filter or the filter in use is coarse, providing no real protection in the particle size range of critical oil films and surfaces. When particles are not removed by filtration or by settling, a lubricant's contaminant level equals the machine's service hours multiplied by the number of particles ingressed per hour (ingression rate). For machines exposed to high ambient dust, particle counts can exceed target levels in just a few hours. After days of exposure, a fluid can turn into more of a honing compound than a lubricating medium.

Ingression and Mass Balance

Even hydraulic systems with good filters are often faced with ingression challenges. To maintain contaminant levels within targets, the filter must remove particles at a rate equal to the ingression rate (mass balance). The lower the target cleanliness level (higher desired cleanliness), the more difficult this becomes. Here's why: In order for a fluid to stay within these high cleanliness targets, particles are not densely packed in the oil but rather are sparsely distributed – few and far between. This means that for every gallon of fluid that enters the filter, there are few particles from that gallon that are available to be removed. Yet the filter must still remove particles at a rate equal to the ingression rate, otherwise the contaminant level will rise. This places increasing demand on the quality and capture efficiency of the filter (percent of particles removed above a certain size).

Also sharply influencing this is the flow rate of the oil entering the filter. The flow provides the necessary conveyance of particles to the filter. If flow rates are low, filters with even 100 percent capture efficiency cannot remove enough particles to keep pace with ingression, causing contaminant levels to exceed targets. The higher the target cleanliness (more dirty oil), the higher the minimum required flow rate for a given filter.

Cost of Excluding Dirt

It is often said that the cost of excluding a gram of dirt is only about 10 percent of what it will cost you once you let it enter the oil. As mentioned, dirt puts stress on additives, the base oil and machine surfaces. So, too, the cost to filter a gram of dirt from the oil is much higher than the cost of filtering a gram of dirt from the air intake/breather.

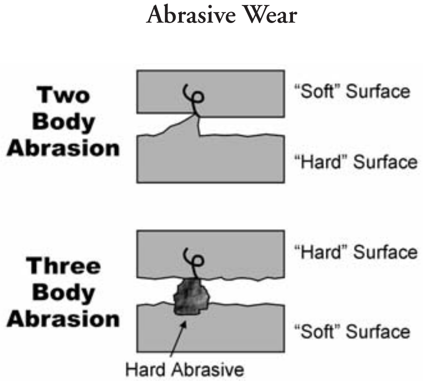

Abrasive Wear

Figure 3-1 Illustrated Examples of Two- and Three-body Abrasion

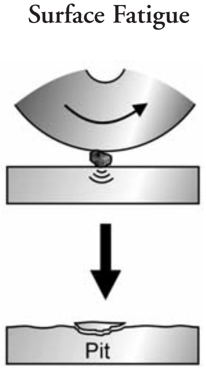

Surface Fatigue

Figure 3-2 Surface Fatigue Wear in Rolling Contacts

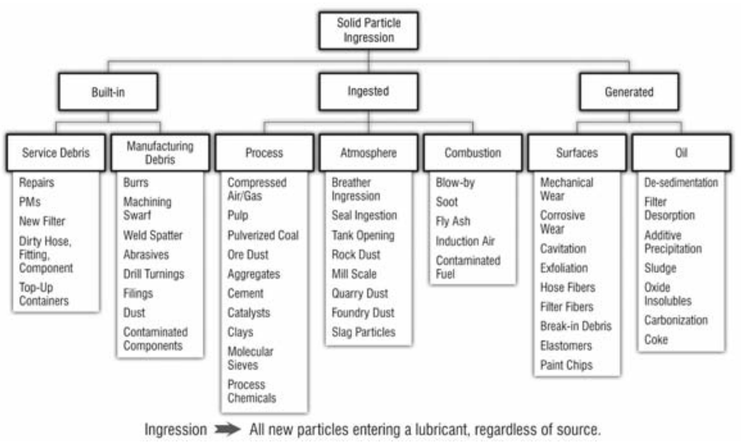


Figure 3-3 Categories of Particle Ingression

The word "ingression" refers to the introduction of particles into lubricants and hydraulic fluids regardless of the source (external and internal). Figure 3-3 organizes common ingression sources into three subcategories: built-in, ingested and generated. Depending on the nature of the machine, the ingression rate and sources can vary considerably. For clean-environment indoor equipment, the primary sources can be from process fluids and internal generation (wear, corrosion, etc.).

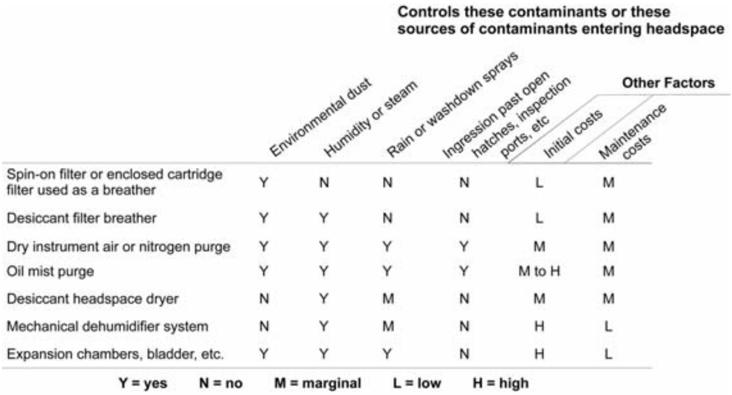
Machines that operate in outdoor work environments can encounter high levels of ambient dust, representing as much as 95 percent of all particles that enter the oil. Machines that operate close to the ground are prone to higher ingression rates than those that operate high in the air (including aviation) or away from the ground altogether (marine). For outdoor machinery, climate conditions have a marked influence on particle ingestion. For instance, rain and damp soil keep particles from becoming airborne. High winds and dry climates do just the opposite.

Controlling Top-End Ingression

For many machines, reducing ingression means reducing top-end ingression – the particles entering through fill ports, vents, breathers, hatches, inspection ports and other headspace openings. There are numerous ways to control top-end ingression, such as:

- **Purge Methods.** This involves the introduction of a clean gas or aerosol into the headspace of the reservoir. A slight positive pressure is maintained to prevent the entry of ambient air. Examples include instrument air purge, oil mist purge and nitrogen purge.
- **Isolation Methods.** Expansion chambers, piston/cylinder reservoirs and bladders have been used to isolate headspace air from ambient air to prevent contamination. One disadvantage is that moisture (humid air) is often unable to escape from the headspace. This also locks moisture into the oil.
- **Filter Breathers.** If reservoirs and sumps can be sealed tightly, such that all air exchanged between the atmosphere and the headspace can be directed through a single port, then high-quality filter breathers can be used to remove dust from incoming air at that port (vent). The quality of the filter (capture efficiency) should be no less than that of the oil filter in use.

Figure 3-4 presents a table of the headspace management options for both particulate and moisture ingression risks. The ingression control strategy needs to correspond to the machine design, operating conditions and exposures.



	Controls these contaminants or these sources of contaminants entering headspace				Other Factors	
	Environmental dust	Humidity or steam	Rain or washdown sprays	Ingression past open hatches, inspection ports, etc	Initial costs	Maintenance costs
Spin-on filter or enclosed cartridge filter used as a breather	Y	N	N	N	L	M
Desiccant filter breather	Y	Y	N	N	L	M
Dry instrument air or nitrogen purge	Y	Y	Y	Y	M	M
Oil mist purge	Y	Y	Y	Y	M to H	M
Desiccant headspace dryer	N	Y	M	N	M	M
Mechanical dehumidifier system	N	Y	M	N	H	L
Expansion chambers, bladder, etc.	Y	Y	Y	N	H	L

Y = yes **N = no** **M = marginal** **L = low** **H = high**

Figure 3-4 Headspace Management Options for Both Particulate and Moisture Ingression

Map Contaminant Ingression Sources

The first step of a contamination control program is to identify a machine's target cleanliness level, as previously mentioned. Next, identify the source and entry points of particles. This generally involves conducting a contaminant ingression study.

Because particles are often internally generated, it's not simply a matter of doing a walkdown inspection to look for top-end ingression points. For many machines, there is a need to examine particles found in used filters, bottom sediment, oil drains and live zone oil samples as a means to determine their origin. This can be done using microscopic methods and by element analysis (testing particles for copper, lead, iron, silicon, etc.). Multiple oil sampling points in circulating equipment can help isolate ingression to certain components like hydraulic cylinders. Additionally, taking particle counts upstream and downstream of filters while the machine is in normal service can be helpful in identifying the approximate ingression rate (number of particles entering per unit time).

Figure 3-5 shows how this information can be used to map the contaminant sources for a hydraulic system. In the hypothetical example, the figure shows particle and moisture entry relative to six contributing sources. Further, the Headspace and Ventilation contributing source shows a breakout of six sub-entry points for these contaminants. This same detailed breakout could be charted for the other main

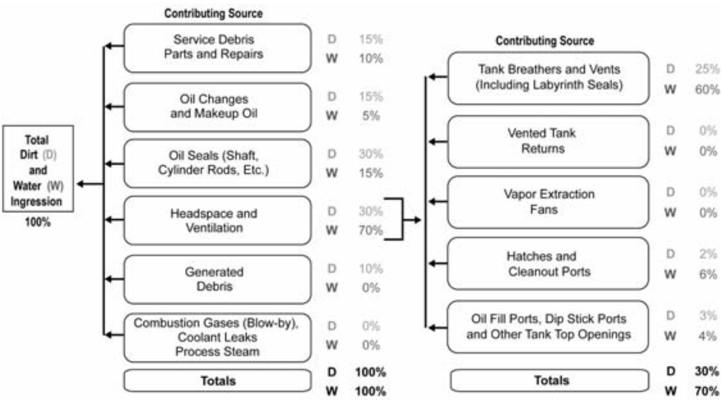

Contributing Source
Service Debris Parts and Repairs
D 15%
W 10%
Oil Changes and Makeup Oil
D 15%
W 5%
Total Dirt (D) and Water (W) Ingression
100%
Oil Seals (Shaft, Cylinder Rods, Etc.)
D 30%
W 15%
Headspace and Ventilation
D 30%
W 70%
Generated Debris
D 10%
W 0%
Combustion Gases (Blow-by), Coolant Leaks Process Steam
D 0%
W 0%
Totals
D 100%
W 100%
Contributing Source
Tank Breathers and Vents (Including Labyrinth Seals)
D 25%
W 60%
Vented Tank Returns
D 0%
W 0%
Vapor Extraction Fans
D 0%
W 0%
Hatches and Cleanout Ports
D 2%
W 6%
Oil Fill Ports, Dip Stick Ports and Other Tank Top Openings
D 3%
W 4%
Totals
D 30%
W 70%

Figure 3-5 Example of a Contaminant Ingression Mapping Chart

contributing sources. Once these sources are understood, plans should be developed and deployed to systematically restrict ingression, starting at the highest ingression points.

Roll-off Cleanliness

Roll-off cleanliness is the level of original cleanliness expected to be achieved when assembling any component or system with clean parts in a controlled manufacturing environment. The purpose of maintaining a high level of roll-off cleanliness is to minimize the overall original system contamination and reduce the premature damage caused to various system components on startup.

Built-in contamination is the inadvertent contamination left in a system or component during initial assembly or system rebuild. The quality and cleanliness of the manufacturing environment is paramount to limiting the amount of built-in contamination. Therefore, an important role of cleanliness starts with control of contamination in the manufacturing environment and associated work and assembly practices. Much like the in-service control of machine contamination, the work zones of a manufacturing facility also should be viewed as "controlled areas". Some of the areas that must be controlled are:

- Assembly, rebuild, cleaning and repair areas
- Component, parts and fluid storage areas
- Shipping and receiving, purchasing, and the supplier areas

Filtration and Particle Removal

To achieve modern contamination control objectives, most machines require filtration or separators. Numerous different filter types and separators are available for removing particles. The performance of these devices is typically evaluated according to the following performance criteria:

- **Filter Stability** – How stable is the filter's performance over time? Unstable filter performance equates to unreliable contamination control (fluctuating particle counts). Many factors influence filter stability, including temperature variation, cold starts, pressure surges and mechanical vibration. The filter's size, design and construction influence its stability.

- **Filter Dirt-Holding Capacity** – This describes the amount of test contaminant a filter can remove, typically in grams.
- **Filter Capture Efficiency** – This defines how effectively a filter can remove particles greater than a given size. This is important information in assessing a filter's ability to meet the machine's cleanliness requirements. It is also important to assess the total cost to filter oil. Filter capture efficiency will be discussed in more detail later.

Particle Filter Construction and Separation Options

The following methods are among the available options for removing particles from oil:

- **Cellulose Fiber Media Filters** – Available in cartridge or spin-on configurations, this common type of filter is equipped with a pleated media made from cellulose filter paper (wood pulp). These filters are generally effective at removing larger particles but often lack performance in the removal of silt-sized particles (less than 5 microns). Cellulose paper media is subject to damage caused by water and high temperature.
- **Micro-fiberglass Media Filters** – Also available in cartridge or spin-on configurations, the performance of micro-glass media filters is typically superior to cellulose fiber filters due to small fiber strand diameter, higher pore density and smaller average pore size. These filters can remove most large particles and many smaller, silt-sized particles from the oil. They offer superior thermal stability and are generally unaffected by the presence of water.
- **Centrifugal Separators** – By spinning the oil at high rotational velocities, suspended particles and other high-density contaminants can be efficiently separated. These separators are generally most effective at removing large particles from low-viscosity oil. Performance is degraded when particles are small, of lower-density or when the oil's viscosity is high.
- **Electrostatic separators** – These devices capture particles by electrostatic precipitation. By creating a high-voltage potential cell (no current

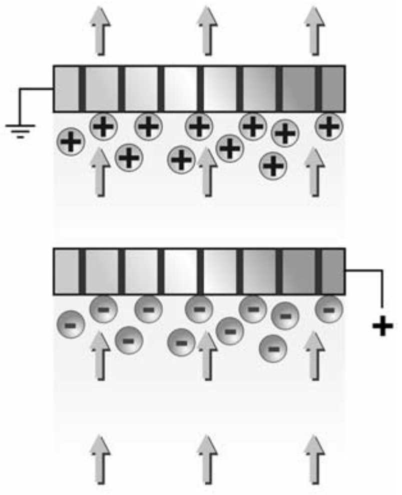


Figure 3-6 Example Particle Removal Method of an Electrostatic Separator

flow), charged particles are attracted to the separation plate with an opposite charge (see Figure 3-6). Electrostatic separators offer excellent performance in the removal of silt-sized particles and insoluble suspensions of oxides and carbon polymers that lead to varnish on component surfaces. Their performance depends upon the dielectric property of the oil and is, therefore, impaired by the presence of water.

Selecting and locating filters and separators to meet cleanliness and reliability objectives is an engineering process, and the details of which are beyond the scope of this book on oil analysis. However, an overview table of the decision steps needed to select filters for circulating oil systems is shown in Figure 3-7.

There are three primary options for locating a filter on a conventional circulating system such as a hydraulic system: pressure line, return line and off line (see Figure 3-8). In rare cases, all three locations have been fitted with filters. If just two locations are selected, it could be any duplex combination of the three options. If just one filter location is fitted with a filter, it is usually either the pressure line or the return line. The following is a discussion of these three locations:

Pressure-line Filtration. Filters located on the pressure line receive the full flow and pressure delivered by the pump. As such, both the filter element and the housing must be designed to handle these often extreme operating conditions. Other unique field and duty-cycle conditions can put stress on the pressure-line filter as well, including vibration, pressure ripple, shock loading and temperature cycling.

Pressure-line filters are often selected to mitigate the risk of tank contamination from being dispersed into sensitive work-end system components. Additionally, pumps in failure mode are protected from shelling out a debris field into downstream components when pressure-line filters are used. Because these filters are more expensive than return-line and off-line filters, the resultant cost per gram of dirt removed is higher as well. Many designers put slightly coarser filter elements (say 15 microns) in pressure-line filter housings to gain their protective attributes, but rely on finer filters (say 3 microns) elsewhere for dirt removal.

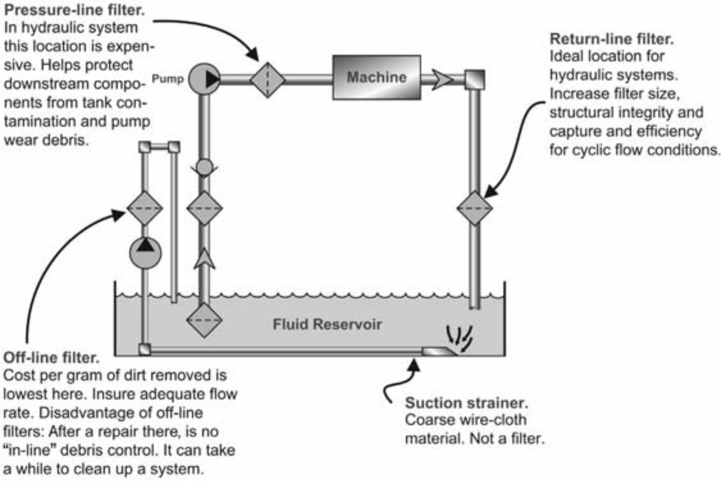
Filter Selection Decisions	Why It Matters	Inputs Needed to Make the Decision
Beta (time-weighted average)	Defines the life cycle particle capture efficiency at certain particle sizes. Helps determine what target cleanliness can be achieved.	Target cleanliness level.
Beta (life cycle minimum)	Defines worst-case capture efficiency. Helps define reliability risk in protecting system.	Contaminant sensitivity of high-risk components – for example, servo valves.
Duty cycle tolerance (surge flow, flow cycling, vibration, shock, etc.)	Some machines produce high duty cycle and, therefore, high risk of losing filtration performance.	Machine design and application information. Other related factors are pressure/flow cycles (frequency and amplitude), temperature extremes, etc.
Dirt-holding capacity	The dirt-holding capacity helps define the service interval (how often filter must get changed) and the average cost to remove a gram of dirt (filter economy).	Ingression rate, maximum permissible size of the filter, importance of filter economy (budget constraints, etc.).
Filter media type	Some filter media types are incompatible with expected service life of the filter, temperature extremes, fluid chemistry, duty cycle and pressure differential.	Information on the fluid, duty cycle, required service interval, temperature extremes, minimum required collapse pressure.
Housing and element size, metallurgy, surface coatings/treatments, maximum allowable operating pressure, ports, canister configuration, mounting brackets/configuration, collapse strength, etc.	Determines whether a filter selection will satisfy filter selection objectives.	Filter location, flow rate at that location, maximum new element differential pressure, maximum required terminal differential pressure, duty cycle, pipe/hose connectors/size/threads, viscosity, fluid type, coldest startup temperature, normal operating temperature.
Need for drainback blocking valves. Need for duplex filtration with switching valve (changeover value)	Relates to whether the filter can be changed on the run and with minimal fluid loss.	Machine operating conditions, frequency of downtime, risk of fluid loss during filter changeouts, etc.
Bypass valve type and setting	Determines what differential pressure permits oil to bypass to avoid starvation, yet risking downstream contamination. Aids in determining the lowest cold-start temperature.	Information on temperature extremes, reliability/safety risks of lubricant starvation, downstream contaminant sensitivity, availability of other filters (serial or parallel).
Filter change indicator and type	Determines the criteria for changing the filter and how the need will be communicated to the maintenace staff.	Reliability/safety risks of lubricant starvation, downstream contaminant sensitivity, availability of other filters (serial or parallel), availability of maintenance staff.

Figure 3-7 Filter Selection Decision Table

Return-line Filtration. Like pressure-line filters, on hydraulic systems, return-line filters are subjected to extreme operating conditions. However, these conditions have unique differences. Instead of high pump pressure and flow, return-line filters generally see only mild line pressures and widely varying flows. The flow rate on the return line is often not defined by the system pump, but rather by load conditions from actuators. Large hydraulic cylinders can induce flow surges that often exceed maximum pump volume by a factor of three or more. Surge-flow conditions can wreak havoc on return-line filter elements, causing structural fatigue and impaired capture efficiency.

Filters specifically designed to resist surge-flow stresses are sometimes specified. In other cases, the solution may simply be the use of oversized filters. The benefit of return-line filters is their downstream proximity to the largest particle ingression sites on most hydraulic systems (cylinder rods ingression past wiper seals). Using return-line filters, these particles can be stripped from the oil before reaching the reservoir. Once particles reach the reservoir, they present high risk to the pump since, for a number of reasons, suction-line filters are not practical.

Off-line Filtration. Off-line filters are a relatively modern alternative or addition to conventional full-flow filters. These filters sit off the main operating system as a side-loop from the reservoir. A necessary supplemental component to the off-line filter is a pump and motor.



Pressure-line filter. In hydraulic system this location is expensive. Helps protect downstream components from tank contamination and pump wear debris.

Return-line filter. Ideal location for hydraulic systems. Increase filter size, structural integrity and capture and efficiency for cyclic flow conditions.

Off-line filter. Cost per gram of dirt removed is lowest here. Insure adequate flow rate. Disadvantage of off-line filters: After a repair there, is no "in-line" debris control. It can take a while to clean up a system.

Suction strainer. Coarse wire-cloth material. Not a filter.

Figure 3-8 Filter Location Options

Because it does not depend on the hydraulic system, it can run independently, even when the main system is off. The following are a few additional benefits and attributes of the off-line filtration option:

- Higher initial cost (pump, motor, valves, piping)
- Constant flow optimizes dirt-holding capacity and capture efficiency for a given type of filter
- Easy to service "on the run" (filter changes, repairs, etc.)
- Heat exchanges can be built in the loop
- Sample ports can be installed for sampling on the run
- Lowest cost to remove a gram of dirt (expensive pressure-line and surge-resistant filters are required)
- Can double for an oil transfer system for adding makeup oil

Filter Performance Testing and Ratings

Modern filters by reputable manufacturers have been tested to assess performance attributes across a range of criteria. These include collapse strength, burst pressures and structural integrity. However, the contaminant-removal characteristics of a filter come from testing done in accordance to standards such as ISO 16889 and ISO 4548/12.

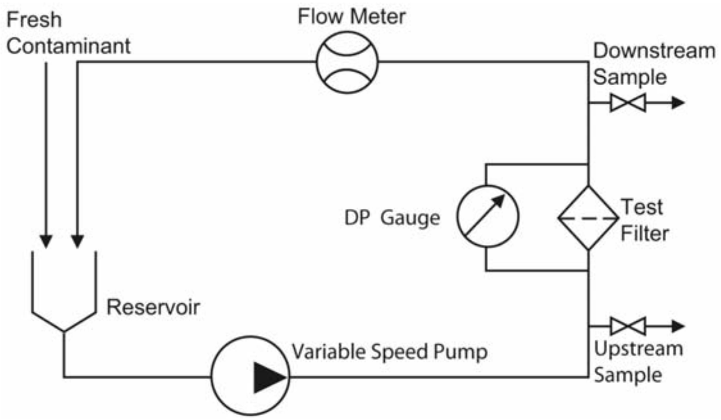


Figure 3-9 Multi-pass Filter Test Stand

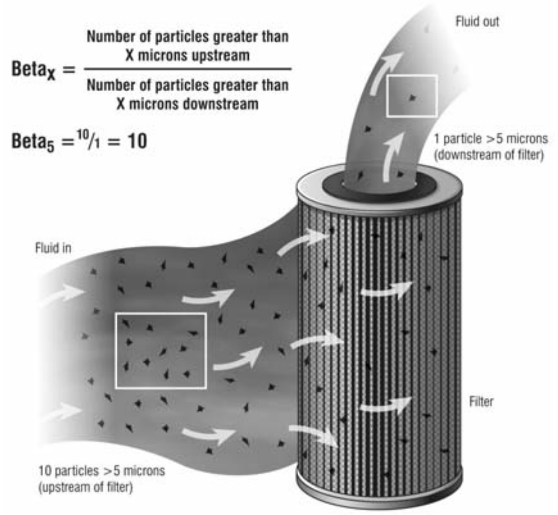

Beta$_X$ =
Number of particles greater than X microns upstream
Number of particles greater than X microns downstream
Beta$_5$ = $^{10}/_1$ = 10
Fluid out
1 particle >5 microns (downstream of filter)
Fluid in
Filter
10 particles >5 microns (upstream of filter)

Figure 3-10 Filtration Ratio (Beta)

Information from this standard includes pressure vs. flow characteristics, dirt-holding capacity and filtration ratio (also known as the Beta ratio). The filtration ratio is a measure of the particle capture performance of a filter at standardized test conditions (maximum rated flow, constant flow, constant temperature, constant contaminant injection rate, standardized test dust and fluid). The simplified schematic of a multi-pass test stand that runs a filter to ISO 16889 is shown in Figure 3-9.

The Beta ratio is calculated as the number of particles above a specific micron size (per unit volume of fluid) upstream of the test filter divided by the number of particles above that same micron size downstream of the filter (see Figure 3-10). The standard calls for the micron size to be reported for filtration ratios of 2, 20, 75, 100, 200 and 1,000.

3.2 Moisture Contamination

Often called the scourge of hydraulic and lubricating machines, water contamination is the second-most destructive contaminant. As depicted in Figure 3-11, water coexists with oil in the following states:

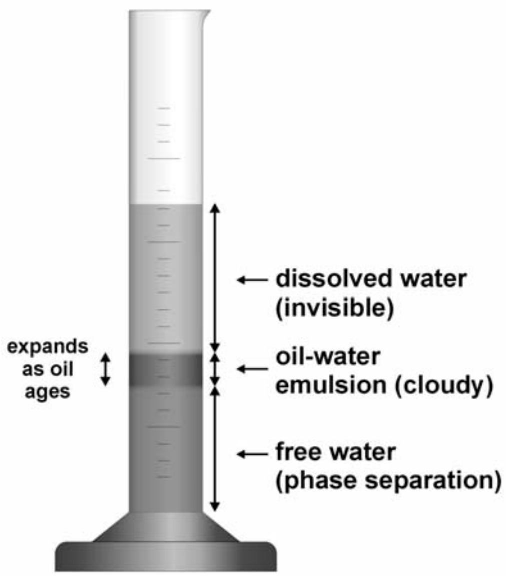
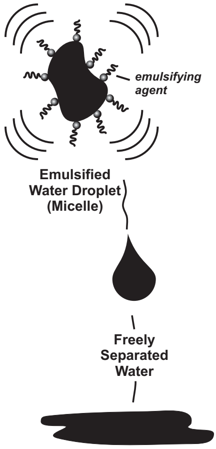


Figure 3-11 Water's Three States of Co-existence with Oil

- **Dissolved** – Oil will dissolve a small amount of water into its chemistry. The volume of water the oil will dissolve depends upon its base stock type, base stock condition, additive package, contaminant load and temperature. New high-purity paraffinic base oil (Group II or III, for instance) that has no additive or perhaps just an oxidation inhibitor will dissolve very little water before reaching its saturation point (maximum amount of dissolved water) – say 100 parts per million (ppm). Conversely, oxidized, low-grade oil that is heavily loaded with polar additives and contaminants will dissolve a larger volume of water before reaching its saturation point. Of course, the saturation point of any lubricant is relative to temperature. As temperature rises, the soluble volume of water rises. As temperature drops, the soluble volume also drops. If the temperature drops below the condensation point, some of the dissolved water will become free or emulsified.

- **Emulsified** – When free (undissolved) water is subjected to shearing conditions present during pumping or caused by the churning of gear teeth or bearings, it is fragmented into small globules that can

Causes of Poor Oil/Water Separation



Ineffective oil/water separation can lead to corrosion, poor lubrication, and rapid oiloxidation and hydrolysis.

Causes of Poor Demulsification:

- Oil mixed with detergents and dispersants (crankcase oil)
- Depletion of demulsifying additives (water washing)
- Oil oxidation (oxide insolubles)
- Oil heavily contaminated (polar impurities)
- Oil contaminated with surfactants (parts coating and process chemicals)
- Oil contaminated with washdown soaps/detergents
- Cold tank temperatures
- Reservoir short-circuiting (insufficient residence time)
- Change in pH of the water

Figure 3-12 Causes of Poor Oil/Water Demulsibility

remain suspended in a stable state in the oil (Figure 3-12). Additives, oxides and contaminants can encourage the stable emulsification of water in oil. Emulsified water produces a hazy, cloudy or milky appearance, depending on the volume entrained. Emulsified water is considered the most harmful due to its high interfacial contact area with the oil and its mobility (ability to be carried by the oil through the machine). Emulsified water can exist as water-in-oil in lower concentrations and as oil-in-water in higher concentrations.

- **Free** – Water is free when it separates from the oil due to inherent insolubility and demulsibility of the two substances and the differences in specific gravity. In mineral oil, free water will settle to tank and sump bottoms. However, certain synthetics have specific gravities (density) above that of water, making it buoyant. Water sheds (settles) more efficiently (also known as demulsibility) from low-viscosity and highly pure oil containing no (or minimal) polar additives. Conversely, free water will not shed efficiently from engine oil due to the high concentration of polar additives. These polar additives include detergents, dispersants, rust inhibitors and anti-wear agents.

Where Water Enters

Like particles, water enters the machine and oil many different ways, but most commonly it is at sites where the machine interfaces with its environment. Below is a summary of water ingression points:

- **Work Environment** – Free water is often present in plant and fleet working environments. Rain, washdown sprays and cooler line leakage provide an opportunity for water to be ingested through seals, vents, reservoir hatches and with new oil.
- **Condensation** – Machines that operate with frequent starts and stops are subject to condensation ingression from the atmosphere. When the temperature rises, the absolute volume of water that the lubricant can dissolve (saturation point) rises. Conversely, when the temperature drops, the saturation point drops and the oil might reach the dew point, or the point at which a fraction of dissolved water transforms to free or emulsified water. When the temperature rises again, the oil absorbs more water and the process continues. Water also condenses on the ceiling and walls of the headspace in tanks and sumps. The condensate can drip into the oil and puddle on the sump floor. In engines, cold temperature operation can condense water vapor from combustion. Finally, water can condense in oil from ineffective steam seals in certain machines.
- **Coolant Leakage** – Coolers often leak due to chemical or erosive wear conditions. When this happens, the coolant water leaks (along with antifreeze, where applicable) directly into the oil.

How Water Affects the Oil

Water reacts with some additives to form precipitants and some chemically aggressive by-products. This reaction is called hydrolysis. Water also acts as a catalyst to promote oxidation, especially in the presence of reactive metals like iron, copper and lead. When free water is allowed to accumulate in sumps and reservoirs, microorganisms can grow. The microbes feed on oil and certain additives and can grow to form thick biomass suspensions. Microbial contamination also leads to corrosion, plugged filters and surface deposits.

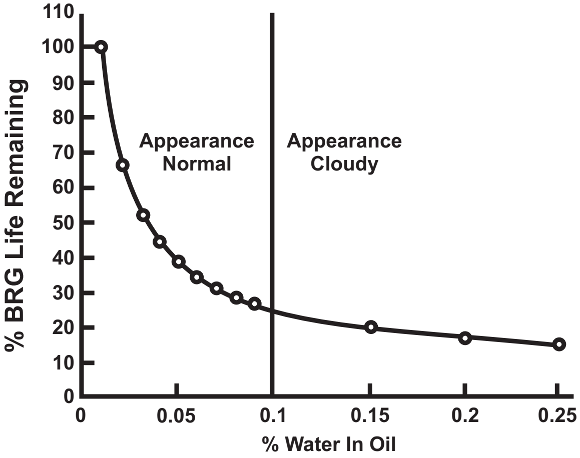


Figure 3-13 Water-induced Premature Bearing Failure

How Water Affects the Machine

Water that is in a free or emulsified state interferes with lubrication by weakening the load-bearing strength of the lubricant film (Figure 3-13), leading to premature wear and failure of bearings, gears, pistons and other wear-sensitive parts. Dissolved water also can cause hydrogen-induced wear and failure of rolling element bearings in a process known as hydrogen embrittlement. Also, water rusts iron and steel surfaces and increases the corrosive potential of acids that attack bearing metals.

Controlling Water Contamination

Once detected, investigate the root cause of water ingression. If the oil's physical and chemical properties are not irreparably damaged, the water can be removed (dehydration) and the oil returned to service. Oil dehydration methods include:

- **Settling Tanks** – Although results vary depending upon the differences in specific gravity and the viscosity of the oil, free water can be removed from oil by providing a good settling location and environment and allowing sufficient time for the settling to occur (see Figure 3-14). Occasionally, heaters are applied to encourage the separation. This method is limited to free water as it is unsuccessful in removing dissolved or emulsified water.

- **Centrifugal Separators** – The settling process can be accelerated when the forces of gravity are magnified using a centrifuge or vortex generator (see Figure 3-15). While more effective than gravity separation, centrifugal separation also fails to remove dissolved water and tightly held emulsions of water in oil. Very often, centrifuges are used

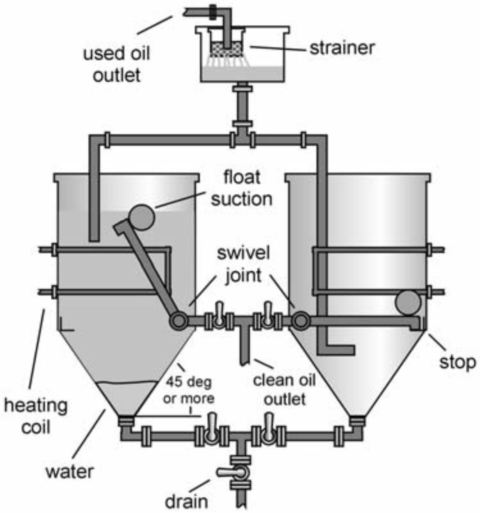


Figure 3-14 Settling Tank Used to Remove Free Water

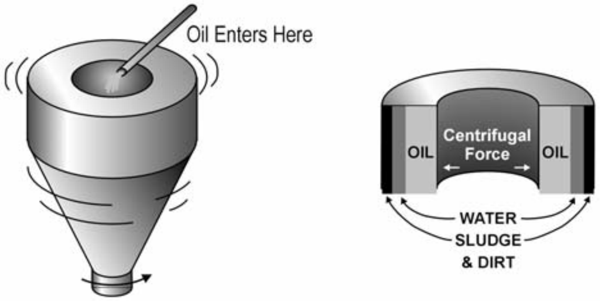


Figure 3-15 Separation of Water and
Other Heavy Contaminants by Centrifugation

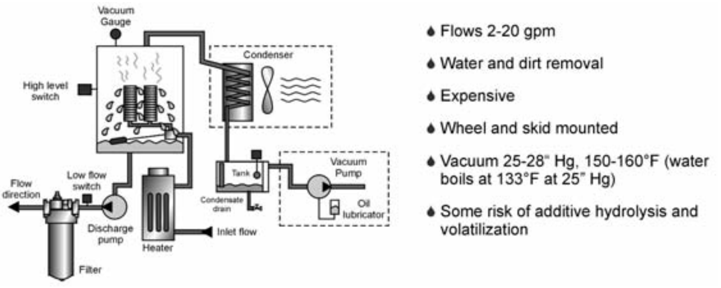


Figure 3-16 Dehydration by Vacuum Distillation

as a first-pass removal of free water, followed by other methods to remove dissolved and emulsified water.

- **Vacuum Distillation** – Water can be effectively boiled out of the oil when the temperature reaches 100° C, but high-temperature exposure of the oil can cause damaging thermal and oxidative stress (see Figure 3-16). Vacuum distillation products can dehydrate the oil without permanent damage to the lubricant by increasing the temperature only modestly and drawing a vacuum to effectively reduce the boiling point of water. They are successful in removing free and emulsified water, plus most of the dissolved water. Vacuum dehydrators are generally large and expensive and, as such, they are typically moved from application to application.

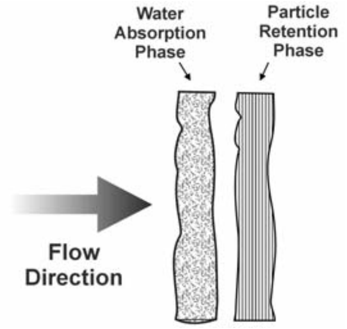


Figure 3-17 Some Super-absorbents can Absorb in Excess of 500 Times Their Weight in Water

- **Polymeric Super-absorbent Filters** – These filters look like conventional spin-on or cartridge-type filters, but they utilize a filter media that is impregnated with a super-absorbent polymer (see Figure 3-17). The polymer absorbs free and emulsified water and forms a gel that is locked tightly into the filter's media. Some versions of these filters remove both water and dirt.

3.3 Fuel Contamination

Fuel contamination occurs primarily in engine crankcase applications. Most engine oils accumulate some fuel (called fuel dilution) during operation. Extended oil drain, improper operation or engine malfunction can lead to an unhealthy buildup of fuel in the lubricant.

Where it Enters

Fuel enters the crankcase as blow-by with combustion gases and from leakage. Blow-by refers to combustion gases from the combustion chamber blowing by the piston rings (usually at the ring gaps) and then entering the crankcase. Abnormal amounts of blow-by occur due to incomplete or ineffective combustion caused by one or more of the following:

- Excessive idling
- Lugging

Diesel Fuel Dilution - Percent	Viscosity in Centistokes at 40° Celsius																			
0	65	75	85	95	110	120	130	140	150	160	175	185	195	205	215	235	260	280	300	325
1	60	70	85	95	105	115	125	135	140	155	165	175	185	195	205	220	245	265	285	300
2	60	70	80	85	95	105	115	125	135	145	155	165	175	180	190	210	225	245	265	280
3	55	65	75	85	95	100	110	120	125	140	145	155	160	170	180	195	210	225	245	265
4	55	65	70	80	90	95	105	110	120	130	135	145	150	160	170	185	195	215	230	245
5	55	60	70	75	85	90	100	105	110	120	130	135	140	150	155	175	185	200	215	220
6	50	60	65	70	80	85	95	100	105	115	120	125	135	140	150	160	175	185	200	210
7	50	55	65	70	75	80	90	95	100	105	115	120	125	135	140	150	160	175	185	195
8	45	55	60	65	70	80	85	90	95	100	110	115	120	125	130	140	150	165	175	180
9	45	50	55	65	70	75	80	85	90	95	100	105	110	115	120	135	140	150	160	170
10	45	50	55	60	70	70	75	80	85	90	95	100	105	110	115	125	130	140	150	155
11	40	45	55	55	60	65	70	75	80	85	90	95	100	105	105	115	125	135	140	145
12	40	45	50	55	60	65	70	70	75	80	85	90	95	95	100	110	115	125	130	135
13	40	45	50	50	55	60	65	70	75	80	80	85	90	90	95	100	110	115	120	130
14	35	40	45	50	55	55	60	65	70	75	75	80	85	85	85	95	100	105	115	120
15	35	40	45	45	50	55	60	65	65	70	70	75	80	80	80	90	95	100	105	110

SAE (crankcase) Viscosity at 40∞ Celsius	
SAE	cSt range
60	276 - 360
50	176 - 275
40	120 - 175
30	76 - 119
20	35 - 75

Figure 3-18 Viscosity Changes from Motor Oil Fuel Dilution

- Defective fuel injection spray pattern or dribbling
- Improper fuel/air ratio

Its Effect on the Oil

Fuel dilution reduces the lubricant's performance in the following ways:

- **Premature Oxidation** – Fuel oxidizes very easily due to the high concentration of aromatic molecules. Their oxidation in the lubricant produces reactive by-products that stress the lubricant's more stable hydrocarbons (saturated molecules), setting off a chain reaction of oxidative failure (sludge, varnish, increased viscosity and organic acids).

- **Loss of Viscosity** – Fuel, being miscible with oil, causes viscosity thinning. As can be seen in Figure 3-18, 10% diesel fuel in a motor oil (SAE 30) reduces the viscosity more than 36% (from 110 to 70 centistokes [cSt]).

- **Additive Dilution** – Fuel doesn't bring any additives to the crankcase. Therefore, the lubricant's additives are proportionally diluted from fuel dilution. In other words, 10% fuel in motor oil reduces the concentration of all additives by 10%.

- **Sulfur Build-up** – Sulfur from some fuels, like diesel, increases the risk of corrosion.

Its Effect on the Machine

Fuel dilution adversely affects the machine in the following ways:

- **Increased Wear** – Viscosity loss and anti-wear additive dilution couple to increase the rate at which mechanical wear occurs.

- **Increased Corrosion** – Sulfuric acid and oxidation-induced organic acids pair up to corrode component surfaces.

- **Fire and Explosion Risk** – High levels of fuel dilution can lead to ignition of the mixture and engine explosion. Likewise, increasing lubricant levels (due to the addition of fuel) can lead to overflow out of the crankcase, creating a fire risk.

Controlling Fuel Dilution

Fuel dilution must be stopped at its source. Once contaminated with excessive fuel, the oil must be condemned.

3.4 Soot Contamination

Soot is a natural by-product of combustion. Extended oil drains or poor combustion lead to abnormal soot accumulation that has harmful effects upon the lubricant and the machine. New Environmental Protection Agency (EPA) requirements to control atmospheric soot and nitrous-oxide (NOX) emissions using exhaust gas recirculation (EGR) will lead to increased soot loading in crankcase oils in the coming years.

Where it Enters

Soot enters the lubricant as blow-by with combustion gases (see Figure 3-19) and is caused by the following:

- **Low Compression** – Produces poor combustion, increasing the rate at which soot is generated.
- **High Fuel/Air Ratio** – Caused by plugged or restricted air filter flow or incorrect mixture settings.
- **Cold Air Temperatures** – Occurs during seasonal operating conditions.

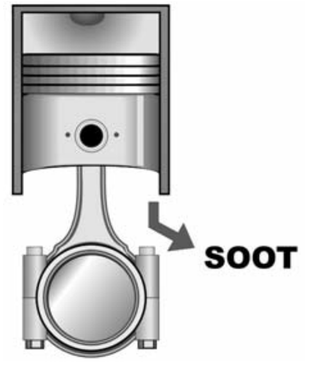


Figure 3-19 Blow-by is a Common Source of Soot Contamination in Motor Oil

- **Lugging** – Pulling an exceedingly high load or operating an engine in too high of a gear.
- **Excessive Idling** – Extended periods of at-rest or severe low speeds during operation.

Its Effect on the Oil

Soot has the following effects on the oil:

- **Dispersancy Loss** – By adsorbing dispersant additive molecules, dispersancy performance deteriorates rapidly when soot ingestion is high, leading to premature oil failure.
- **Anti-wear Performance Loss** – Anti-wear additive molecules adsorb to soot surfaces, rendering them unavailable to protect machine components.
- **Increased Viscosity** – Soot suspended in the oil increases the oil's viscosity. This causes increased temperature and slows the flow of lubricant to machine components.

Its Effect on the Machine

Soot affects the machine in the following ways:

- Premature filter plugging
- Increased abrasive wear (typically where boundary lubrication occurs such as cam/cam-following wear zones)
- Deposit formation, sludge and oil-way blockage

Controlling Soot Contamination

Soot must be controlled by dealing with the cause of ingestion relating to engine combustion efficiency and causes of excessive blow-by. Once soot has contaminated the oil, little can be done to remove it. Some success in removing soot using low-flow, bypass filters and centrifuges have been reported. However, removing soot by these methods can usually only occur after the soot particles have become agglomerated (loss of dispersancy), at which time deposits on machine surfaces may have already occurred.

3.5 Glycol Contamination

Glycol frequently contaminates crankcase lubricants and other systems that utilize a glycol and water mixture for cooling. Always present and flowing, glycol is a constant threat to leak into the lubricant, especially in crankcase applications.

Where it Enters

Typically, glycol leaks into the crankcase due to the following reasons:

- Defective seals
- Cavitation of the cylinder liner
- Corrosion degradation of the cylinder liner
- Damaged cooler core

Its Effect on the Oil

Glycol has the following effects on the oil:

- Forms gels and emulsions
- Increases viscosity
- Increases oxidation
- Forms acids (e.g., formic and glycolic acids)
- Reacts with the detergent additives to forms “oil balls” (hard, abrasive reaction products)

Its Effect on the Machine

Glycol has the following effects on the machine:

- **Increased Wear** – This is caused by: (1) the general poor lubricating quality of the oil, (2) a change in oil viscosity, (3) the formation of oil balls, (4) particle-induced abrasion from plugged oil filters, and (4) oil starvation from restricted oil flow (related to sludge and deposit formation).

- **Increased Corrosion** – Corrosion increases due to the acidic environment glycol creates in the lubricant.
- **Filter Failure** – Glycol clogs filters prematurely.

Controlling Glycol Contamination

Glycol must be controlled at its ingestion point. It can't be easily removed once the oil is contaminated except with an oil change. Under severe occurrences of glycol contamination, flush the crankcase or sump before refilling with lubricant.

4. Oil Sampling Methods

Oil sampling is the most critical aspect of oil analysis. Errors in obtaining a representative sample impair all further oil analysis efforts. There are two primary goals in obtaining a representative oil sample:

- **Maximize Data Density** – Simply stated, samples should be taken in such a way that there is the most information per milliliter of oil possible. This information relates to such criteria as cleanliness and dryness of the oil, depletion of additives, and the presence of wear particles being generated by the machine. For instance, taking samples downstream of filters would be contrary to this sampling goal since the filter would effectively remove much of the data before it could get to the sample bottle.
- **Minimize Data Disturbance** – Samples should be extracted in such a way that the concentration of information is uniform, consistent and unaltered by the sampling process. It is important to make sure that the sample does not become contaminated during the sampling process. This can distort the data, making it difficult to distinguish what was originally in the oil from what has come into the oil during the sampling process. For example, sampling oil with a dirty sample bottle can result in data disturbance (a false positive in this case).

To ensure good data density and minimum data disturbance in oil sampling, consider the following factors, each of which is discussed in detail later in the chapter:

- **Sampling Location** – Not all potential sampling locations in the machine will produce the same data. Some locations are upstream of data-generation sites (a bearing, for instance) and others are downstream (a more rich sample). Some machines require multiple sampling locations to answer specific questions related to the machine's condition, location of a problem and severity. Optional locations (called secondary samples) can be used on exception only for troubleshooting purposes.

- **Sampling Procedure** – The quality of the procedure by which a sample is drawn is critical to the success of oil analysis. Sampling procedures should be documented and followed uniformly by all members of the oil analysis team. This ensures consistent use of the correct procedure and helps to properly institutionalize oil analysis within the organization. It also provides a recipe for success to new members of the team.

- **Sampling Hardware** – The hardware used to extract the sample should not disturb sample quality but should aid it. It should be easy to use, clean, rugged and cost-effective.

- **Sample Bottle** – The type, size and cleanliness of the oil sample bottle help assure that a representative sample is achieved.

It is always advised to spend the time and money to make sure machinery is properly fit with the sampling hardware to ensure these goals in oil sampling are achieved.

4.1 Sampling Locations on System Returns

There are several rules for properly locating oil sampling ports on circulating systems. These rules cannot always be precisely followed because of various constraints in the machine's design, application and plant environment. However, the importance of proper oil sampling cannot be overstated as a priority in oil analysis. As closely as possible, follow the rules outlined in this section. These rules will be expanded and further discussed later.

- **Turbulence** – The best sampling locations are highly turbulent, sometimes referred to as live zones. These are locations where the fluid is moving to help hold wear debris and contaminants in uniform suspension prior to sampling. For example, in circulating oil systems, don't sample where oil flows in a straight line, but instead sample where it is turning and rolling within the pipe. Sampling valves located at right angles to the flow path in long straight sections of pipe can result in "particle fly-by." This can lead to particle counts exhibiting a "false negative" (i.e., a sharply lower reading than actual). Particle fly-by can be avoided by locating sampling valves at elbows and sharp bends in the flow line.

- **Ingression Points** – Where possible, in circulating systems locate sampling ports downstream of the components that generate wear debris and/or ingress contaminants (e.g., particles and moisture). Return lines and drain lines heading back to the tank usually offer the most representative levels of wear debris and contaminants. Once the fluid reaches the tank, concentrations can become greatly diluted or diminished (from settling and evaporation).

- **Filtration** – Filters and separators are contaminant removers; therefore, they can extract valuable data from the oil sample. Always locate primary sampling valves upstream of filters, separators, dehydrators and settling tanks unless the performance of the filter, for example, is being specifically evaluated. In such a case, both upstream and downstream sampling valves will be necessary.

- **Drain Lines** – In unflooded drain lines where fluids are mixed with air, locate sampling valves where oil will travel and collect. On horizontal piping, this will be on the underside of the pipe. Sometimes oil traps must be installed, like a goose neck, to concentrate the oil in the area of the sampling port.

On circulating systems, look first at return lines or drain lines that direct fluid back to a reservoir. These systems include pressurized returns and drains such as those in hydraulic systems or forced circulating lubrication systems where there is a scavenger pump returning the oil back to the tank. There also are drain-line applications where the oil returns to the tank by gravity. Sometimes these drains are vented (non-flooded), like those commonly seen on steam turbines, paper machines and some compressors.

As previously noted, the ideal location for sampling circulating systems is on the drain and return lines (see Figure 4-1). Such locations allow you to obtain a sample of the oil before it returns to the tank and always before the oil goes through a filter. If the oil is permitted to return to the tank before it is sampled, then the information in the sample becomes diluted, potentially by thousands of gallons of fluid in large lubricating and hydraulic systems. Return-line sampling helps identify active debris generation. Conversely, debris that enters the reservoir tends to accumulate over weeks and months. As a result, samples from reservoirs may not accurately represent the current conditions of the machine.

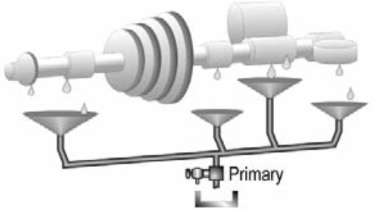


Figure 4-1 Return-line Sampling Locations are Preferred for Circulating Oil Systems

Figure 4-2 is an example of a large lubrication system with oil being supplied to a set of bearings. The oil flows down from these bearings by gravity through a manifold or header, then back to the tank. Here, a number of optional sampling locations are identified. Some locations are labeled with an "S", meaning they are secondary sampling locations (used for localizing problems and troubleshooting).

The primary sampling location, labeled "P", is on the header of this drain line just before the oil is returned to the tank. The primary sample is the one that is analyzed at routine intervals (e.g. monthly). The secondary sample is not analyzed routinely but only after a problem has been reported from the primary sample or other condition monitoring technology.

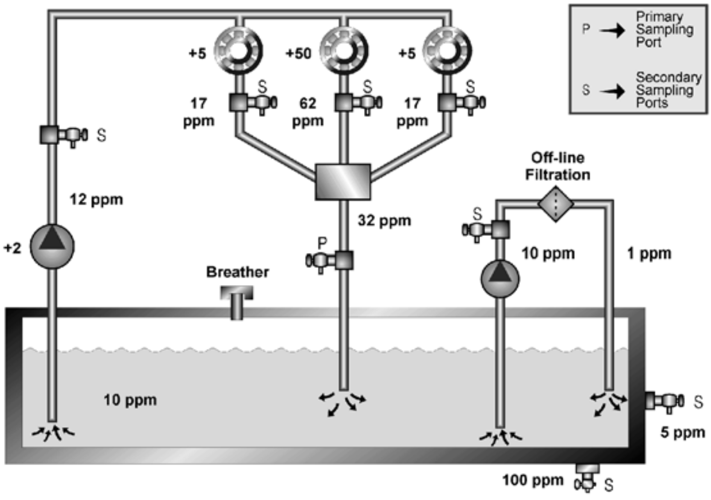


Figure 4-2 Example Locations of Primary and Secondary Sample Ports

Many potential problems can be detected from the primary sample. For example, if the bearings are experiencing abnormal wear, or if there are high levels of moisture, particles, process debris or chemicals being pulled into the oil from seals or vents, you will get the clearest indication of this from the drain-line sampling port. Likewise, you can verify that the oil meets the required levels of cleanliness and dryness. It also verifies that the viscosity and all other physical properties of the oil are within the target range. This is considered the primary sampling location because it is representative of the oil that is being delivered to the bearings and also picks up particles that the bearings add to the oil (wear debris and contaminant ingestion).

When an abnormal machine condition is detected from the primary sampling point, the next step is often to sample from secondary points to isolate the problem. In this case, on Figure 4-2, there is 32 ppm represented at the primary sampling point (for this example, assume that this number represents the amount of iron in the oil). This high reading leads you to use the secondary sampling points to identify the source of the increased iron concentration. In this example, 17 ppm is being generated in each of the outside bearings while the center bearing is producing 62 ppm. The supply fluid of this system shows just 12 ppm. It is obvious that the middle bearing is producing the wear debris and needs immediate attention. Diagnostic efforts can now be focused on that component.

In this example, had we relied entirely on oil sampled from the tank, we would have observed only 10 ppm because of dilution of the bearing debris by the large volume of oil, particle settling and the presence of the off-line filter that removes much of wear debris from the oil. Likewise, if we were to sample the bottom of the tank, we would see a very high concentration of sludge and water; in this case, there is 100 ppm of iron. This, of course, is historic information and probably has nothing to do with the current condition of the bearings.

In summary, the drain line provides the primary sampling point. If there is an abnormal reading or an over-limit alarm, take samples from the individual bearing drains. Also, obtain a sample on the supply fluid. By comparing these samples, you can determine a good estimation of what the problem is and from where it is being generated.

Figure 4-3 illustrates a hydraulic system with pressurized fluid. Again, the primary sampling location is the return line. But in this case, because there is a return-line filter, take the primary sample just upstream of this filter. If the filter is doing its job (cleaning particles from the fluid), it is a data remover. If a sample is taken on the downstream side of the filter, the filter can capture critical information about the condition of the machine before it has a chance to reach the sample bottle. If the filter itself is a problem – and is in bypass, has collapsed or is defective – the sample upstream of the filter will ultimately be contaminated just like the fluid on the downstream side.

In this case, the sampling port on the return line (upstream of the filter) is showing 262 ppm of wear metal or contaminant. If a sample is taken at both of the secondary locations, it is seen that there is 260 ppm flowing downstream of the hydraulic motor and 270 ppm downstream of the cylinder. This suggests that the particulate material entering the fluid is shared by both of these actuators.

By following the flow upstream and sampling downstream of the pump, it is clear that the 250 ppm is coming from the pump. This means that there is either a problem with the pump, or that dirty oil is

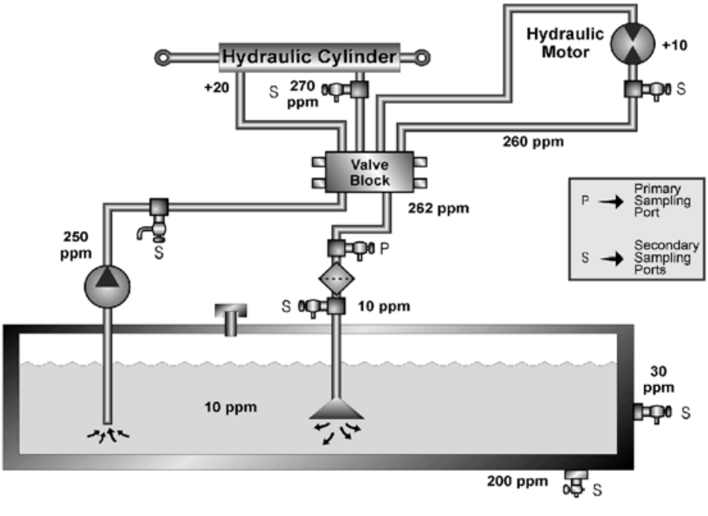


Figure 4-3 Primary and Secondary Sampling Locations on a Common Hydraulic System

being supplied to the pump from the tank. A sample drawn from the tank reveals the low reading of 10 ppm, confirming that the pump is the problem. With the problem localized, diagnostic and corrective actions can be focused entirely upon the hydraulic pump.

4.2 Live Zone Sampling from Circulating Systems

When a sample is taken from a line in a circulating system, it is referred to as a "live zone" sample. You can take measures during the sampling process to improve the quality and effectiveness of the live zone sample. What follows is a summary of do's and don'ts.

Do:

1. Sample from the system's turbulent zones, where the fluid is moving and the oil is well mixed.
2. Sample downstream of the equipment after it has completed its primary function(s), such as lubricating a bearing or a gear or has passed through a hydraulic pump or actuator.
3. Sample systems during typical working conditions, on the run and under normal applications. Try not to sample after an oil change, filter change or at some time when the fluid wouldn't represent typical conditions.
4. Where required, employ secondary sampling locations to localize problems.

Don't:

1. Sample from dead pipe legs, hose ends and stand pipes where the fluid isn't moving or circulating.
2. Sample after filters or separators.
3. Sample when the machine is cold and hasn't been operating or has been idling.
4. Sample from laminar flow zones (lack of fluid turbulence). The best way to insure the fluids are turbulent and mixed during the sampling process is to sample from elbows instead of straight lengths of pipe (see Figure 4-4).

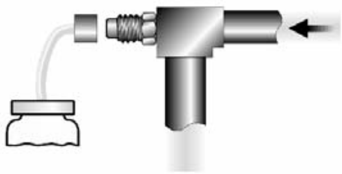


Figure 4-4 Sampling on a Elbow Helps Insure Fluid Turbulence

4.3 Sampling from Pressurized Lines

When samples need to be taken from pressurized feed lines leading to bearings, gears, compressors, pistons, etc., the sampling method is somewhat simplified. Figure 4-5 shows four different configurations.

- **Portable High-Pressure Tap Sampling** – The upper-most configuration on Figure 4-5 is a high-pressure zone where a ball valve or needle valve is installed and the outlet is fitted with a piece of stainless steel helical tubing. The purpose of the tubing is to reduce the pressure of the fluid to a safe level before it enters the sampling bottle.
- **Minimess Tap Sampling** – This alternative requires that a minimess valve (or similar sampling device) be installed, preferably on an elbow. The sample bottle has a tube fitted with a probe protruding from its cap. The probe attaches to the minimess port, allowing the oil to flow into the bottle. There is a vent hole on the cap of the sample bottle so that when the fluid enters the bottle, the air can expel or exhaust from the vent hole. This particular sampling method requires lower pressures (less than 500 psi) for safety.
- **Ball Valve Tap Sampling** – This configuration requires the installation of a ball valve on an elbow. When sampling, the valve should be opened and adequately flushed. Extra flushing is required if the exit extension from the valve is uncapped. Once flushed, the sample bottle's cap is removed and a sample is collected from the flow stream before closing the valve. Take care when removing the bottle cap to avoid the entry of contamination. This technique is not suitable for high-pressure applications.
- **Portable Minimess Tap Sampling** – This option requires installing a minimess onto the female half of a standard quick-connect coupling.

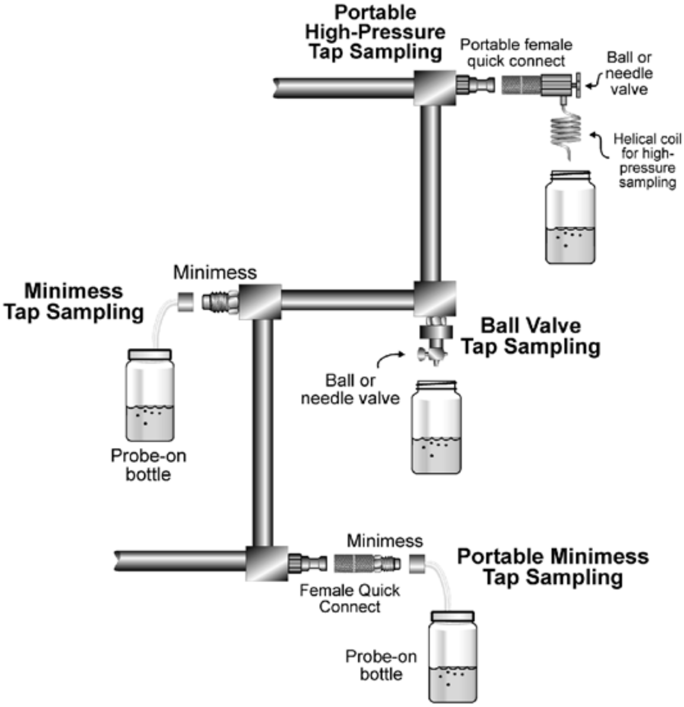


Figure 4-5 Common Options for Sampling on Pressurized Lines

This assembly is portable. The male half of a quick-connect is permanently fitted to the pressure line of the machine at the desired sampling location. To sample, the portable female half of the quick-connect is snapped onto the male piece affixed to the machine. To sample, the bottle's probe tip is pressed onto the minimess valve to induce fluid flow into the bottle. In many cases, these male quick-connect couplings are pre-existing on the equipment. Always use helical coil, previously described, on high-pressure lines.

Figure 4-6 shows a minimess valve installed on hydraulic machinery. This valve is properly equipped with a dust cover so that the internal opening of the sampling port is protected from debris. The cap, when fitted with an O-ring, also serves as a secondary seal in the unlikely event that the minimess valve should fail.

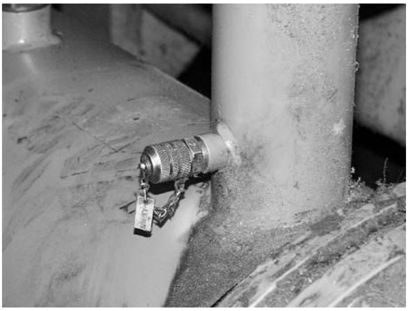


Figure 4-6 Photo of a Live-zone Minimess Valve on a Hydraulic System

4.4 Sampling From Low-pressure Circulating Lines

Occasionally, a drain line, feed line or return line is not sufficiently pressurized to take a sample from a standard sample valve alone (e.g. a minimess). In such cases, sampling requires assistance from a vacuum pump equipped with a special adapter, allowing it to attach momentarily to the valve used in sampling. A minimess valve has a mechanical check that is actuated by a probe. With the adapter threaded onto the minimess valve, fluid can be drawn by vacuum into the bottle (see Figure 4-7).

4.5 Sampling Wet-sump Circulating Systems

Frequently, there are applications where a drain line or a return line can't be accessed or no such line exists. Basically, these are wet-sump applications where the sump within the casing serves as the reservoir. Oil free-falls by gravity to the sump. Examples of wet-sump machines include:

- Diesel engines
- Circulating gearboxes
- Some circulating compressors

In these applications, because there is no return line, fluid must be sampled from the pressurized supply line leading to the gearing and the bearings (see Figure 4-8). Collect the sample before the filter, if one exists.

The best place to sample engine crankcase oil is just before the filter (see Figure 4-9). Install the sampling valve between the pump and

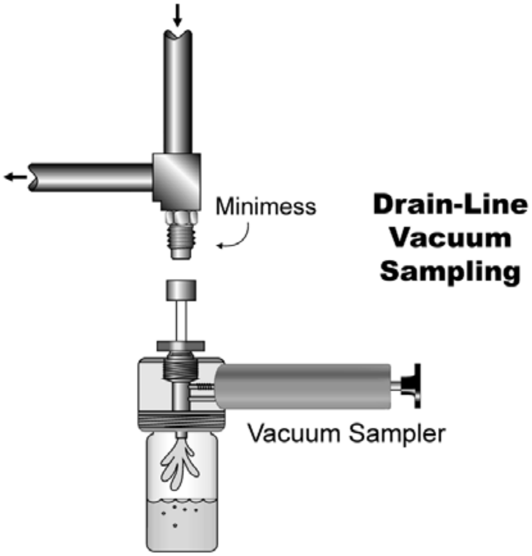


Figure 4-7 A Vacuum Pump is Used to Assist Oil Being Sampled from a Low-pressure Line

filter. This sample location is highly preferred over sampling from a drain port or using a vacuum pump with the tube inserted through the dipstick port. Another example of a wet sump involving circulation is shown in Figure 4-10, where there is a side loop that is often referred to as a kidney-loop filter. This off-line circulating system provides an ideal location to install a sampling valve between the pump and filter. Use a ball valve or minimess valve so that the fluid under pressure flows easily into the sample bottle without disturbing the operating or filtration system.

4.6 Sampling Non-Circulating Systems

There are numerous examples where no forced circulation is provided and a sample must be taken from a system's sump or casing. This often must be done with "in-service" equipment on the run. Ring-, collar- or bath-lubricated bearings are examples. So, too, are splash- and flinger-lubricated gearboxes. All of these machine configurations increase the challenge of obtaining a representative sample.

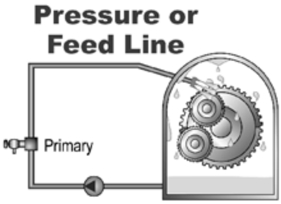


Figure 4-8 Live-zone Sampling Location on a Wet-sump Circulating System

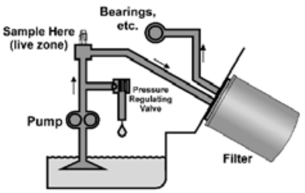


Figure 4-9 Sampling Location on a Diesel Engine

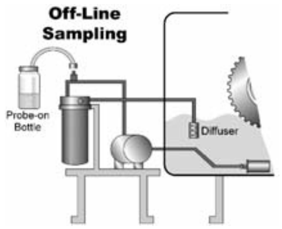


Figure 4-10 Off-line Circulating Oil Sampling Location

The most basic method for sampling such sumps is to remove the drain plug from the bottom of the sump, allowing an amount of fluid to flow into the sample bottle. For many reasons, this is not an ideal sampling method or location. Most important is the fact that bottom sediment, debris and particles (including water) enter the bottle in concentrations that are not representative of what is experienced near or around where the oil lubricates the machine. Due to this stratification, avoid the drain port sampling method if at all possible (except for the purpose of inspecting for water and sediment).

You can greatly improve drain-port sampling by using a short length of stainless steel tubing, extending inward and up into the active moving zone of the sump (see Figure 4-11). This ball valve and tube assembly can, in many cases, be threaded into the drain port and can be easily removed to facilitate periodic draining of the oil.

A third option is called drain port vacuum sampling. With this method, a minimess valve is installed as previously described, but instead of fluid passing into a sample bottle by gravity, it is assisted by a vacuum sampler (see Figure 4-12). This is particularly helpful when the oil is highly viscous and difficult to sample through a narrow tube

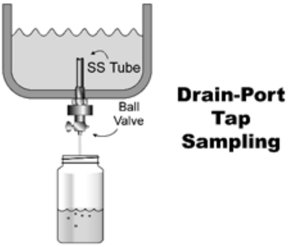


Figure 4-11 Drain Port Samples Aided by the Use of Stainless Steel Pilot Tubes

by gravity alone. During the sampling process, the connector on the end of the plastic tube of the vacuum pump is threaded onto the minimess valve. Vacuum is produced by the pump pulling oil downward from the case into the sample bottle.

Still another method for sampling a non-circulating gearbox or a bearing housing is to use a portable oil filtration system such as a filter cart. In this case, the filter cart is attached to the sump (see Figure 4-13). Here, the cart circulates the fluid off the bottom of the sump and back into the sump. In order to keep from cleaning the oil before sampling (which removes important data from the sample), the filters must be bypassed using a directional valve. Allow the fluid to become homogenous by circulating the fluid for about five to 15 minutes, depending on: (1) the size of the unit, (2) the amount of fluid in the unit, and (3) the flow rate of the filter cart. Once sufficient mixing has occurred, a sample can be taken from the sampling valve (installed between the pump and the filter). With the sample drawn, the filters can be re-engaged to clean the fluid.

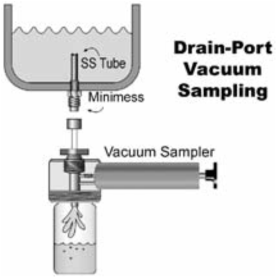


Figure 4-12 Drain Port Sampling Aided by a Vacuum Pump

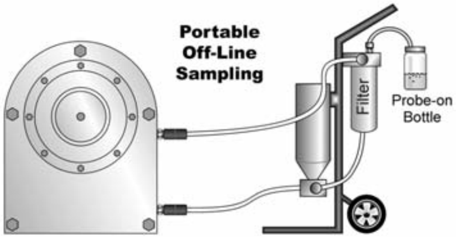


Figure 4-13 Off-line Sampling Using a Filter Cart

4.7 Drop-Tube Vacuum Sampling

One of the most common methods for sampling a bath- or splash-lubricated wet sump is to use the drop-tube vacuum sample method. With this method, a tube is inserted through a fill port or dipstick port and lowered into the sump cavity – usually about midway into the oil level (see Figure 4-14). This sampling method has a number of drawbacks and should be avoided if other sampling methods, as previously described, can be used instead. Here is a summary of the risks and problems associated with drop-tube vacuum sampling:

- **Tube Location** – A tube that is directed into the fill or dipstick port is extremely difficult to control. The tube's final resting place is hard to predict, resulting in samples being taken from different locations each time. There is always a risk of the tube actually going all the way to the bottom of the sump, where debris and sediment is picked up.
- **Drop-Tube Contamination** – There is considerable concern that the tube will scoop up debris from the sides of the casing as it is

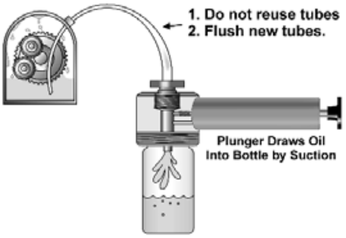


Figure 4-14 Wet Sump Sampling Using the Drop-tube Method

being inserted. Also, the tube itself may be contaminated due to poor cleanliness control during handling and storage.

- **Large Flush Volume** – The drop-tube method substantially increases the volume of fluid that must be flushed in order to obtain a representative sample. For some small sump systems, this results in nearly an oil change. Likewise, if the removed volume of fluid is not replaced, the machine might be restarted with inadequate lubricant volume.
- **Particle Fallout** – For most systems, a shutdown is required to deploy the drop-tube method. This means that production must be disturbed for the sake of oil sampling, or sampling frequency must suffer because of operations priorities. Neither situation is ideal. Likewise, particles begin to settle and stratify according to size and density immediately upon shutdown, compromising the quality of oil analysis.
- **Machine Intrusion** – The drop-tube method is intrusive. The machine must be entered to draw a sample. This intrusion introduces the risk of contamination, and there is always the concern that the machine might not be properly restored to run-ready condition before startup.

Whenever drop-tube sampling is used, consider it a sampling method of last resort. However, there are situations when no other practical method of sampling is available. The following are the best and worst applications for drop-tube vacuum sampling:

Best:

- Tank and reservoir sampling requirements
- Crankcase oils, if a live zone sampling port is not available
- Applications where particle counting, large-particle wear debris and moisture trends are not required

Worst:

- Gearbox and bearing sumps
- Large reservoirs with poor circulation
- Critical applications
- Where reliable trends for particle counts, large-particle wear debris and moisture are routinely required

In the case where drop-tube vacuum sampling must be used on circulating systems, the best location to get the sample is between the return line and the suction line (Figure 4-15). This is known as the short circuit. Even in cases where there is baffling in the tank, the sample needs to be taken from the most direct flow zone between this return line and suction line. Ideally, this will be as close to where the return line discharges into the reservoir. If there is baffling, it should be on the return side of the baffle.

In order to insure that the plastic tube is lowered to the same location each time, it can be fitted with a weight, attached to the end of the tube, where a specific length of tube is lowered into the tank. An easier way is to attach the tube to a metal or plastic rod using wire or twist-ties (Figure 4-16). Then, measure a stand-off on the bottom of

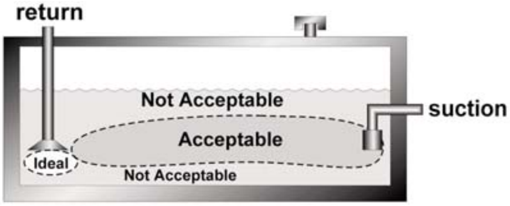


Figure 4-15 Drop-tube Sampling in Tank Short Circuit

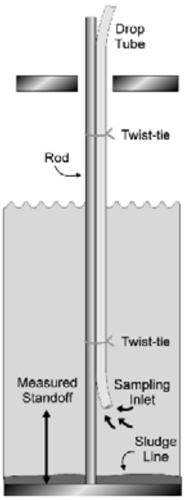


Figure 4-16 Using a Rod to Control the Drop-tube Fluid Intake Location

the rod so that the rod is lowered to the tank floor and the end of the tube is a fixed distance above. This "measured stand-off" is to be consistently used each time a sample is taken.

4.8 Sampling Bottles and Hardware

An important factor in obtaining a representative sample is to make sure the sampling hardware is completely flushed prior to obtaining the sample. This is usually accomplished using a spare bottle to catch the purged fluid. It is important to flush five to 10 times the dead-space volume before obtaining the sample. All hardware that the oil comes into contact with is considered dead space and must be flushed, including:

- System dead-legs
- Sampling ports, valves and adapters
- Probe-on sampling devices
- Adapters for using vacuum sample extraction pumps
- Plastic tubing used for vacuum pumps (this tubing should not be reused to avoid cross-contamination between oils)

An assortment of sampling bottles is commonly used in oil analysis. Select an appropriate bottle for the application and the tests that are planned. Consider the following parameters when selecting sample bottles:

- **Size** – A number of different sizes of sample bottles are available. Bottle size varies from 50 milliliters (or about two ounces of fluid) to 200 ml. The most common bottle size is 100 ml. Where a considerable number of different tests are required, a 200 ml bottle (or two 100 ml bottles) may be required. Coordinate with the laboratory to select the bottle size that will provide a sufficient fluid volume to conduct all of the required tests and leave some extra (retains) for storage in case a rerun is necessary.

  Another consideration in selecting the bottle size is the fact that the entire volume of the bottle should not be filled with fluid during the sampling process. Only fill a portion of the sample bottle. The unfilled portion, called the ullage, is needed to allow proper fluid agitation by the laboratory to restore even distribution of suspended particles and water in the sample. A general guideline for filling bottles is as follows:

  - ○ **Low Viscosity (ISO VG 32 or less)** – Fill to approximately three-fourths of the total volume.
  - ○ **Medium Viscosity (ISO VG 32 to ISO VG 100)** – Fill to approximately two-thirds of the total volume.
  - ○ **High Viscosity (over ISO VG 100)** – Fill to approximately one-half of the total volume.

- **Material** – Bottles are available in several materials. Here is a review of the most common bottle materials:
  - ○ **Plastic Polyethylene** – This is an opaque material similar to a plastic milk jug. This type of sampling bottle presents a drawback because the oil can't be visually examined after the sample is obtained. Important properties of the oil can be immediately learned from a visual inspection such as moisture contamination, air contamination, sediment, darkness, brightness, clarity and color.
  - ○ **PET Plastic** – Modern sample bottles are made of PET (polyethylene terephthalate) plastic due to its chemical compatibility with most base oils and additives, the fact that it is clear, its strength (fracture resistance), its wide availability and its low cost. The primary disadvantage of using PET is the risk that it will melt or become soft when sampling high-temperature fluids (greater than 200° F).
  - ○ **Glass Bottles** – These bottles tend to be more expensive, are heavier, and there is the risk of breakage during the sampling process. One advantage with glass bottles is that they can be cleaned and reused over and over. The cleanliness of glass bottles often exceeds that of plastic bottles.
- **Cleanliness** – One of the most important considerations in selecting a sample bottle is to make sure it is sufficiently clean. Determine the bottle's required cleanliness level in advance. The bottle supplier

should provide, with each bottle order (or upon request), a certificate of cleanliness that is based upon random testing of the bottles per ISO 3722. The report should identify the mean and standard deviation for the lot from which the shipped bottles were taken. Bottles can be classified according to their contribution to the particle count into the following cleanliness categories:

- **Clean** – Fewer than 100 particles greater than 10 microns per ml of fluid.
- **Super Clean** – Fewer than 10 particles greater than 10 microns per ml of fluid
- **Ultra Clean** – Less than 1 particle greater than 10 microns per ml of fluid.

The selection of the bottle cleanliness depends heavily on the target cleanliness of the fluids being sampled. Fluids of assigned high-cleanliness targets (high-pressure hydraulics, for instance) need a correspondingly high bottle cleanliness for sampling (ultra clean, for instance). Modern oil analysis programs typically specify bottles to be 10 times cleaner than the fluid target cleanliness for the same volume.

4.9 Important Tips for Effective Oil Sampling

To achieve "bull's eye" oil analysis data, where oil sampling and analysis produce the most representative and trendable information, follow these basic sampling tactics:

1. Machines should be running in application during sampling. That means sampling when machines are at normal operating temperatures, loads, pressures and speeds on a typical day. If that is achieved, the data will be typical and representative as well, which is exactly what is desired.

2. Always sample upstream of filters and downstream of machine components such as bearings, gears, pistons, cams, etc. This will ensure that the data is rich in information that properly reveals the health of the machine and contaminant ingression. It also ensures that no data (such as particles) are being removed by filters or separators.

3. Create specific “best practice” written procedures for each system sampled. This ensures that each sample is extracted in a consistent and correct manner. Written procedures also help new team members quickly learn the program.
4. Ensure that sampling valves and sampling devices are thoroughly flushed prior to taking the sample. Vacuum samplers and probe-on samplers should be flushed, too, and if there are any questions about the cleanliness of the bottle itself, it should also be flushed.
5. Make sure that samples are taken at proper frequencies and that the frequency is sufficient to identify common and important problems (more on this is coming). Where possible, especially with crankcase and drivetrain samples, record the hours on the oil. This can be a meter reading or some other record identifying the amount of time that the oil has been in the machine. If there has been any makeup fluid added or any change to the oil such as the addition of additives, a partial drain or anything similar, communicate this information to the lab.
6. Forward samples immediately to the oil analysis lab after sampling. The properties of the oil in the bottle and the oil in the machine begin to drift apart the moment after the sample is drawn. Quickly analyzing the sample helps insure that quality and timely decisions are made.

4.10 Oil Sampling Frequency

The objective of oil analysis, like condition monitoring in general, is to find bad news quick. The objective of proactive maintenance is to manage bad news away. The machine and oil will generally give off silent alarms when problems first occur. In time, as the severity increases, these alarms are no longer silent, and even the most rudimentary condition monitoring methods can reveal the problem. Of course, at this point, a great deal of damage has probably occurred. It is likely too late to arrest the problem on the run; the machine may have to be torn down and repaired.

One of the extraordinary benefits of oil analysis is its incredible sensitivity to these silent alarms and the detection of incipient failures and faults. The methods of doing this successfully are discussed in later chapters. However, it is a very basic principle that you can't hear an alarm unless you are listening for it. Stated another way, you can't catch a fish unless your hook is in the water. Unlike other machine condition monitoring techniques that employ monthly testing, many oil analysis programs are based on annual or semi-annual sampling. This sampling infrequency compromises the powerful proactive and predictive capabilities of oil analysis.

Scheduled sampling intervals are common in oil analysis. The frequency may be keyed to drain intervals or operating hours. Figure 4-17 lists commonly recommended intervals based on operating hours for different machine classes.

Proper selection of sampling frequency must be adjusted to consider the following machine and application-specific criteria:

A. **Penalty of Failure** – Consider safety, downtime costs, repair costs and general business interruption costs. This relates to the consequences of failure.

B. **Fluid Environment Severity** – Operation and fluid environment conditions influence the frequency and rate of failure progress. These include pressures, loads, temperature, speed, contaminant ingression rate and system duty cycle severity. This relates to the probability of failure.

Machine Type	Hours
Diesel engines – off-highway	150
Transmission, differentials, final drives	300
Hydraulics – mobile equipment	200
Gas turbines – industrial	500
Steam turbines	500
Air/gas compressors	500
Chillers	500
Gearboxes – high-speed/duty	300
Gearboxes – low-speed/duty	1,000
Bearings – journal and rolling element	500
Aviation reciprocating engines	25-50
Aviation gas turbines	100
Aviation gearboxes	100-200
Aviation hydraulics	100-200

Figure 4-17 Commonly Recommended Oil Sampling Frequencies

C. **Machine Age** – For most machines, the chances of failure are greatest during break-in and after major repairs and overhauls. Likewise, the risk increases as a machine approaches the end of its expected life. Increase sampling frequency during these periods.

D. **Oil Age** – Infant oils and old oils are the highest risk. Infant oils are those that have been recently changed and are less than 10% into remaining useful life (RUL). Occasionally, the wrong oil is put into the machine during a change, or the new oil's condition is unsatisfactory for service (defective or mixed). Aged in-service oils can show trends that suggest additive depletion, the onset of oxidation or high levels of contamination. Adjust sampling frequency accordingly.

Risk is often defined as the probability of failure multiplied by the consequence of failure. Oil sampling and analysis is a means of controlling risk. This relates closely to how frequently we need oil analysis information (sampling frequency). In the just-stated four criteria, A addresses the consequences of failure while B-D address the probability of failure. They all have to be viewed collectively to make the best sampling frequency decision.

4.11 Registering Equipment For Oil Analysis

For those samples sent to outside oil analysis laboratories, complete and submit the necessary machine registration information to the laboratory. The registration should include machine description, machine history, environment and application information, plus lubricant description and specifications. What follows is a list and discussion of registration information to include:

- **Machine Identification Name or Number** – This could be an asset number, a serial number or a name. If the component to be sampled has more than one sample point, an additional identifier must be used to distinguish it from other sample locations.
- **Unit Type** – This identifies the component that is being sampled. Unit type is the most misidentified part of many equipment lists, and it is the most critical item of information from the standpoint

of interpretation. The more information provided, the more specific the analyst can be in interpreting the data. For example, "compressor" is not a valid unit type; "inboard compressor roller bearing oil" is (assuming more than one oil system or sampling point exists). "Hydraulic press brake" is not a valid unit type; "high-pressure vane pump hydraulics" is. Many labs have tables of standards based on specific detailed unit types. If the identification is not specific enough, it may mean that the sample will go through a "generic" table of standards. Therefore, it is usually worth the effort to try to obtain specific information on the unit to be sampled.

- **Manufacturer and Model of Machine or Component** – If the component is a centrifugal pump, for instance, you need the make and model of the pump. If it is a hydraulic system, you need the make and model of the hydraulic pump. This information is helpful in identifying the metallurgy and the ranges of wear metals that can be expected under normal conditions. If available, provide specific information on machine metallurgy, seal materials, surface treatments, etc.
- **Fluid Manufacturer, Fluid Type (Name) and Grade (ISO or SAE, for instance)** – A complete identification of the fluid is nearly as important as the component information. Many labs use tables of standards against which used oil physical and chemical properties are compared. If an oil type is not properly identified, it will be compared to the wrong standard, leading to erroneous conclusions.
- **Operating Conditions** – Collateral information about the application and the environment in which the machine must operate is beneficial to the analyst during evaluation of the oil analysis data. These include speeds, shock loads, standby service, duty cycle severity, etc.
- **Work Environment and Exposures** – This would include mine site, steel mill, high elevation, extreme cold, etc., and close-proximity potential contaminants (gamma radiation, coal dust, wood pulp, H2S, salt water, high sulfur fuel, etc.).
- **Lubricant Application Knowledge** – This would include total oil volume, operating oil temperature, cooler/heater use, circulating, splash, etc.

4.12 Sample Bottle Labels and Identification

The use of sample bottle labels is more than simply an identification system. The label and/or accompanying documentation identifies key information about the sample, the machine and the required tests (including any special instructions). While a great deal of information is supplied during registration on machine and component histories, changes are always occurring, many of which affect the oil analysis results. Here is a list of common information that needs to be supplied with the oil sample (either on the label or in accompanying documentation):

- Machine identification
- Sample point
- Date sampled
- Hot or cold running conditions
- Hour meter (or approximate level of machine usage since the last sample taken)
- Last fluid change (hours on oil)
- Last addition of makeup fluid and amount
- Last major service, repair or overhaul
- Last filter change
- Reported machine/fluid abnormalities by operator or technician (foam in sightglass, varnish in reservoir, leakage, bottom sediment, etc.)
- Requested test slate, including any required special or exception tests

Many software packages provide for automatic printing of bottle labels. While this is very convenient, the importance of supplying information related to current conditions is equally valuable to maximizing the benefits of oil analysis. Some of the items in the just-mentioned list relate to provenance on historic and current operating information. Often, this is communicated on a standard form that accompanies the sample bottle and is placed in the mailer or package along with the sample bottle. As the samples are logged into the computer by the lab, the information on the form is an input as well. Then, the analyst has a complete picture of historic and current condition of the machine to consider in the evaluation of the oil analysis data.

5. Oil Testing and Analysis

New lubricant analysis is a broad field comprised of hundreds of individual tests that reveal meaningful information by assessing one or more properties of a lubricant. Many of the tests measure or characterize a wide range of chemical, physical and performance properties and are used for quality control, product development and product performance classification.

The objectives of used oil analysis, our focus, differ substantially from new oil analysis, although many of the tests are very similar or identical in nature. The objectives of used oil analysis are: (1) to evaluate the condition or age of oils that are in service, (2) to detect and measure harmful foreign suspensions (contaminants), and (3) to evaluate the condition of the machine being lubricated. In machine condition monitoring applications, the lubricant serves merely as the carrier of the information that is generated by the machine in the form of wear debris.

In used oil analysis, a small number of tests are performed regularly to support important machine and lubricant decisions in the field of condition-based maintenance. This chapter provides an overview of these common oil analysis tests and serves as the foundation for Chapter 6, where evaluative processes and information management techniques are discussed.

5.1 Reasons for Performing Oil Analysis

In lubricant analysis, testing plans are defined based on the questions that need to be answered about the lubricant, the machine and the operating conditions. Because there are a large number of possible tests, these questions need to be given careful consideration. Because lubricant testing involves specific costs to the asset owner, the value gained in getting specific answers to the questions must be weighed against these costs. The following are examples of questions that may need to be answered:

Lubricant Type/Quality Questions:

- Has the appropriate lubricant been specified?
- Is the specified lubricant being used?
- What is the quality and condition of newly delivered lubricants?
- Have two incompatible greases or lubricants been mixed?

Lubricant Health/Condition Questions:

- Have any critical additives become depleted or impaired?
- Has the base oil been damaged by oxidation, hydrolysis or thermal degradation?
- Has there been a change in interfacial tension affecting air release, foaming and demulsibility properties?
- Has the oil's viscosity changed due to evaporation, shear, radiation, contamination or various chemical reactions?
- What is the residual life of the lubricant?
- Is a lubricant in a storage container fit for service?

Lubricant Contamination Questions:

- Has the lubricant been cross-contaminated (mixed) with other fluids or lubricants?
- Has the lubricant become contaminated with fuel, soot, dirt, water, process chemicals or coolant?
- Has the lubricant been damaged by radiological contamination? Is it a hot sample?

Wear and Fault Detection Questions:

- Is there incipient evidence of abnormal wear?
- Which component or machine surface is generating the wear?
- What is the tribological cause of the wear?
- Does the oil contain evidence of abnormal operational or mechanical wear conditions such as misalignment or over-loading?
- How severe (advanced) or threatening is the wear?

Miscellaneous Failure Root Cause Questions:

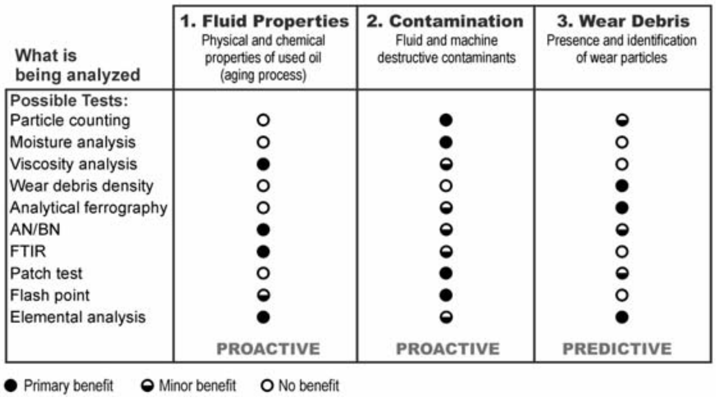
- Is the oil prone to laying down surface deposits, varnish and sludge?
- Is the oil highly acidic with suspended corrosion agents?
- Has there been sabotage or criminal activity associated with the condition of a machine and lubricants?
- Does a new machine have manufacturing defects?

Maintenance, Operations and Commissioning Questions:

- Does a filter need to be changed or is there need to service a separator?
- Is there internal or external leakage?
- Has a machine been properly installed (commissioned)?
- Is there a need to perform certain internal inspections during a shutdown period?
- Has a bearing been over-greased or under-greased?
- Is there evidence of abnormal operating temperatures, pressures or duty cycle?
- Is it time to decommission a machine?
- Has a machine been properly repaired or rebuilt?

In its simplest and most basic form, lubricant analysis is performed to improve the quality of machine and lubrication maintenance decisions. When well designed and implemented, many of the just-mentioned questions can be answered without excessive expense or complexity. This is best accomplished by directing the testing program around three important categories of lubricant analysis:

- **Fluid Properties Analysis** – This category of oil analysis deals with the assessment of the chemical, physical and additive properties of the oil. Its primary goals are to define the remaining useful life (RUL) of the lubricant as well as to confirm that the correct lubricant is currently being used. It also can detect mixed lubricants.



What is being analyzed	1. Fluid Properties Physical and chemical properties of used oil (aging process)	2. Contamination Fluid and machine destructive contaminants	3. Wear Debris Presence and identification of wear particles
Possible Tests:			
Particle counting	○	●	◒
Moisture analysis	○	●	○
Viscosity analysis	●	◒	○
Wear debris density	○	○	●
Analytical ferrography	○	◒	●
AN/BN	●	◒	◒
FTIR	●	◒	○
Patch test	○	●	◒
Flash point	◒	●	○
Elemental analysis	●	◒	●
	PROACTIVE	PROACTIVE	PREDICTIVE

● Primary benefit ◒ Minor benefit ○ No benefit

Figure 5-1 Three Categories of Used Oil Analysis

- **Contamination Analysis** – Contaminants are foreign energy or substances that enter a lubricant and machine from the environment or are generated internally. Contamination compromises machine reliability and promotes premature lubricant failure. Oil analysis ensures that goal-driven targets for contamination control are maintained.

- **Wear Debris Analysis** – When components wear, they generate debris in the form of small particles. The lubricant is usually the first recipient of this wear debris due to its close proximity to the frictional surfaces where the debris was formed. Monitoring and analyzing the generated debris enables technologists to detect and evaluate abnormal conditions such that effective and timely maintenance decisions can be made and implemented.

Common used oil analysis tests and their benefits to the three categories of oil analysis are tabulated in Figure 5-1.

When the design of a lubricant analysis program is optimized, you must consider many factors. These include such things as:

- Sample frequency
- Sampling procedure
- Selection of primary and secondary sampling points

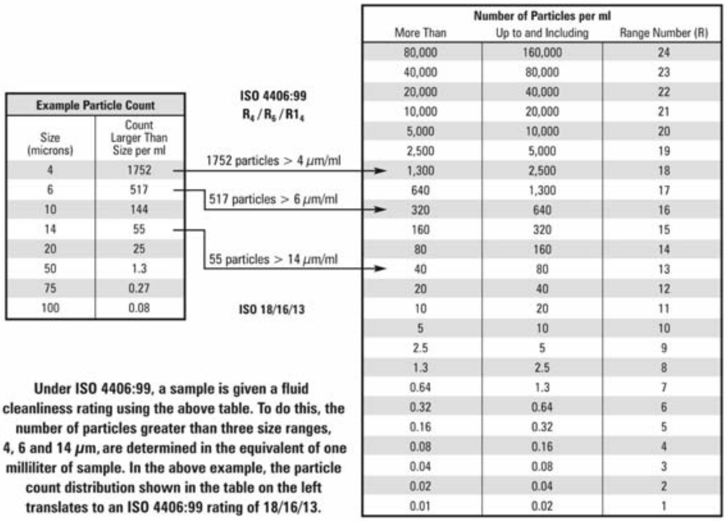
- Streamlined onsite tests
- Routine laboratory tests
- Exception tests and criteria for conducting them
- Alarming strategy
- Precision and quality of data
- Turnaround time
- Data presentation format and software
- Technology integration factors (vibration analysis, infrared imaging, etc.)
- Skill level of onsite analysis
- Thoroughness of machine walkdown inspections

Collectively, all of the listed factors can influence the ability to detect problems in a lubricant analysis program. There also are cost factors to be weighed in associated with each of these factors. In many cases, advice from experts may be justified. It may be beneficial to consult with lubricant suppliers, machinery OEMs, laboratory analysts and lubricant analysis professionals.

5.2 Review of Common Used Oil Analysis Tests

5.2.1 Particle Counting. Particle counting is considered to be one of the most valuable test methods in fluid analysis, and its use dates back to the 1960s. The particle count test reports the number of particles above specified size ranges (in microns) per fluid volume (usually per 1 ml or 100 ml). Also, particle concentration and distribution data may be expressed in terms of ISO 4406:99 Cleanliness Codes (Figure 5-2) or by other less frequently used codification systems such as the revised SAE AS 4059E (formerly NAS 1638).

Particles can be counted manually using optical microscopy (ISO 4407 and ASTM F312-97). In this method, an aliquot of fluid is passed through a membrane. Afterward, particles on the membrane are manually counted under a microscope. The method is similar to the patch test procedure discussed later. There also are commercial methods avail-



ISO 4406:99
$R_4 / R_6 / R1_4$
1752 particles > 4 µm/ml
517 particles > 6 µm/ml
55 particles > 14 µm/ml
ISO 18/16/13

Example Particle Count	
Size (microns)	Count Larger Than Size per ml
4	1752
6	517
10	144
14	55
20	25
50	1.3
75	0.27
100	0.08

Number of Particles per ml		
More Than	Up to and Including	Range Number (R)
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1

Under ISO 4406:99, a sample is given a fluid cleanliness rating using the above table. To do this, the number of particles greater than three size ranges, 4, 6 and 14 µm, are determined in the equivalent of one milliliter of sample. In the above example, the particle count distribution shown in the table on the left translates to an ISO 4406:99 rating of 18/16/13.

Figure 5-2 Cleanliness Codes under ISO 4406:99

able that enable membranes to be optically scanned and digitally analyzed for particle size, count and shape.

Most laboratories use automatic particle counters, which can report a particle count or ISO Code in just a couple of minutes. The two methods are laser optical (ISO 11500) particle counters and pore-blockage (BS 3406 & ISO/DIS 21018). Optical particle counters direct a laser light source at passing particles in the sensor cell (see Figure 5-3). The amount and frequency of light blockage is measured by a photodiode. This signal is converted to particle size and count by the use of standardized calibration methods.

Pore-blockage particle counters use calibrated screens through which the sample flows during a test (Figure 5-4). The profile of the pressure rise or flow decay, caused by particle blockage of the screen's pores, is measured. This profile is mathematically converted to an estimated particle

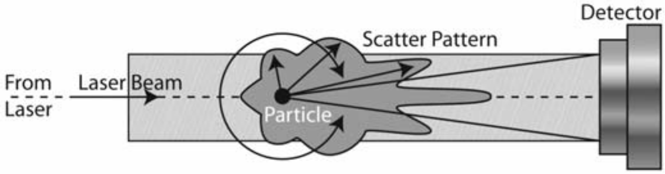


Figure 5-3 Light-blockage Particle Counter

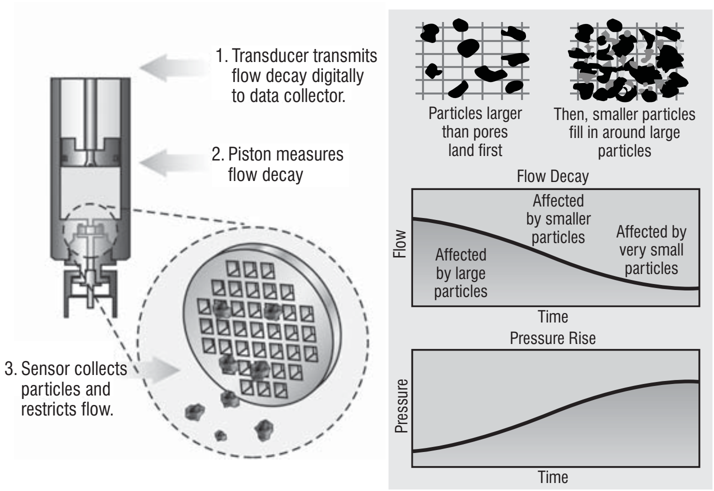

1. Transducer transmits flow decay digitally to data collector.
2. Piston measures flow decay
3. Sensor collects particles and restricts flow.
Particles larger than pores land first
Then, smaller particles fill in around large particles
Flow Decay
Flow
Affected by large particles
Affected by smaller particles
Affected by very small particles
Time
Pressure Rise
Pressure
Time

Figure 5-4 Pore-blockage Particle Counter

count or ISO Code. Some modern particle-counting technologies have the ability to characterize particle shape, as well. With this added information, interpretation of the source, type and severity of the particles can be estimated.

Because of the differences between particle-counting methods (manual, laser and pore-blockage), as expected, there will be differences in results on the same samples. The reasons for this are many and should not be a point of major concern by users if sample preparation and instrument procedures are used correctly. These methods are not absolute measurements but instead estimate size and concentration using standard practice and assumptions. Regardless of the method, it is recommended that the same method be always used to ensure that results are consistent and repeatable. In the right application with the right procedure, most methods are very suitable in the context of maintenance and machine reliability.

What follows are common causes for non-conforming particle count readings:

- **Sampling Error** – Poor control over sampling procedures will result in false positive or false negative particle count readings depending on the nature of the sampling process failure. It is always advised to resample and retest when a high or low particle count is observed to eliminate sampling error from the list of possible causes.

- **Instrument Error** – A particle counter is subject to calibration-related errors like any instrument. Regularly verify the calibration of the instrument.
- **Testing Procedure Error** – You must aggressively agitate samples with a paint shaker or other suitable method before testing commences to evenly disperse the particles in the oil. Likewise, when using an optical particle counter, completely remove or dissolve entrained air and suspended water prior to testing.
- **Dirt Ingestion** – Dirt entering the system through seals, breathers and new oil will lead to an increased particle count. Diagnose this according to the flow chart in Figure 5-5 .

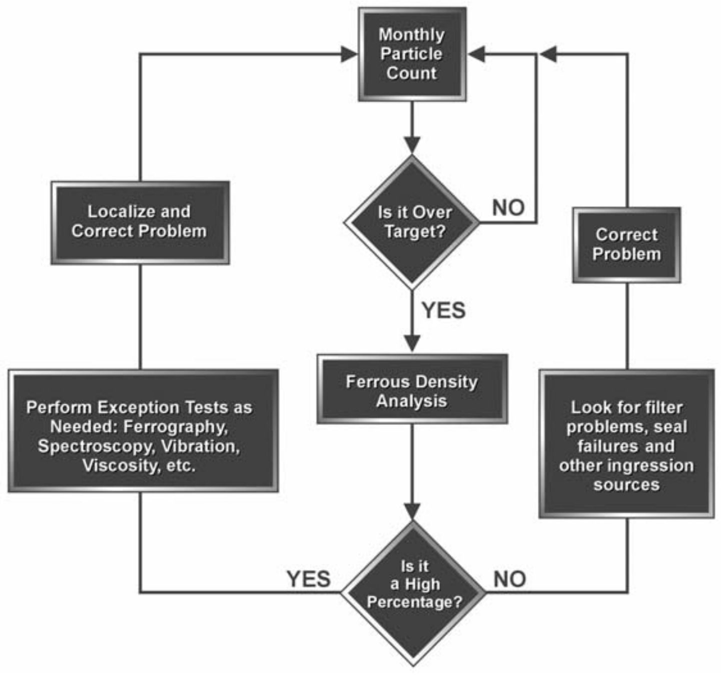

Monthly Particle Count
Is it Over Target?
NO
YES
Ferrous Density Analysis
Is it a High Percentage?
YES
NO
Localize and Correct Problem
Perform Exception Tests as Needed: Ferrography, Spectroscopy, Vibration, Viscosity, etc.
Correct Problem
Look for filter problems, seal failures and other ingression sources

Figure 5-5 Particle Count Diagnostics

- **Filter Failure** – When a filter is full and in bypass, or fails in some way, the particle count will increase. Diagnose this according to the flow chart in Figure 5-5.
- **Generated Wear** – When machine components are abraded or fatigued, wear particles are released into the oil, causing an increase in particle count. Diagnose this according to the flow chart in Figure 5-5.

When particle contamination is monitored and reported routinely, not only is proactive maintenance generally achieved, but also many of the goals of predictive maintenance. As such, particle counting is an important first line of defense in machinery reliability. Because of its value, it is not uncommon to find organizations testing the cleanliness of their oils as frequently as weekly, especially for high-criticality machines.

The following are common proactive and predictive uses for particle counting and analysis in condition monitoring:

Proactive Maintenance:

1. Routinely verify that in-service oils are within targeted cleanliness levels
2. Check the cleanliness of new oil deliveries
3. Quickly identify failed or defective filters
4. Confirm that seals and breathers are effectively excluding contaminants
5. Confirm that systems are properly cleaned and flushed after repair
6. Confirm that new hydraulic systems are cleaned and flushed before use (roll-off cleanliness)
7. Identify the improper use of dirty top-up containers and poor maintenance practices
8. Identify the need and timing for portable filtration systems

Predictive Maintenance:

1. Identify early stage abnormal machine wear
2. Identify the location/source of abnormal wear by multi-point isolating methods
3. Verify the effectiveness of corrective maintenance and botched repair jobs
4. Monitor machine break-in progress by wear particle generation
5. Identify abnormal rust and corrosion debris generation
6. Serve as an effective screen for wear debris analysis (e.g., analytical ferrography)

Applicable particle count standards: ISO 11171, ISO 4406, ISO 11500, ASTM D6786, FTM 3012, FTM 3010, ISO 4407, BS 3406 and ISO/DIS 21018

5.2.2 Viscosity. Kinematic viscosity is a measure of a fluid's internal resistance to flow under gravitational forces. It is determined by measuring the

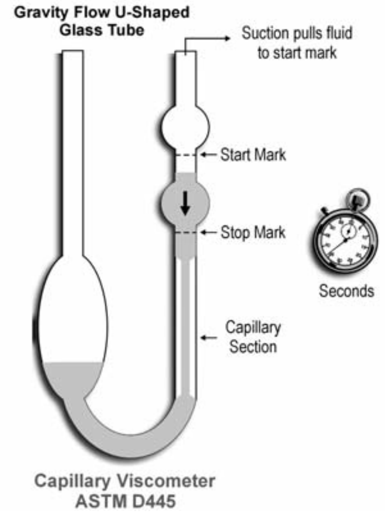

Gravity Flow U-Shaped Glass Tube
Suction pulls fluid to start mark
Start Mark
Stop Mark
Seconds
Capillary Section
Capillary Viscometer ASTM D445

Figure 5-6 Illustration of a Kinematic Viscometer

ISO VG viscosity grade	Midpoint viscosity cSt @ 40°C	Kinematic viscosity limits cSt @ 40°C	
2	2.2	1.98	2.42
3	3.2	2.88	3.52
5	4.6	4.14	5.06
7	6.8	6.12	7.48
10	10	9	11
15	15	13.5	16.5
22	22	19.8	24.2
32	32	28.8	35.2
46	46	41.4	50.6
68	68	61.2	74.8
100	100	90	110
150	150	135	165
220	220	198	242
320	320	288	352
460	460	414	506
680	680	612	748
1000	1000	900	1100
1500	1500	1350	1650

Figure 5-7 ISO Viscosity Grade Chart

time, in seconds, required for a fixed volume of fluid to flow a known distance by gravity through a capillary within a calibrated viscometer at a closely controlled temperature (ASTM D445 or ISO 3105). This value is converted to standard units such as centistokes (cSt) or square millimeters per second (mm^2/sec). Viscosity reporting is only valid when the temperature at which the test was conducted also is reported – e.g., 32 cSt at 40° C (see Figure 5-6).

Most industrial lubricants are classified according to ISO standardized viscosity grades (ISO 3448). As shown in Figure 5-7, the midpoint of each viscosity grade is a 50% increment above the previous grade (with some rounding). For instance, the ISO VG 15 is 50% higher than the previous grade of 10, and so forth. The viscosity grades are based on kinematic viscosity at 40° C. An oil is said to be "in grade" if its viscosity is within +/- 10% of the midpoint viscosity at 40° C.

Viscosity affects equipment operation, friction losses and the oil film thickness in bearings. Its measurement and trending is, therefore, critical to used oil analysis. Even modest changes in viscosity may adversely influence the lubricant's performance and stability, possibly causing metal-to-metal contact and wear. Change in a lubricant's viscosity also is a common symptom of a host of other problems. As such, a viscosity trend excursion may be the first symptom of a far more serious problem.

The rate of viscosity change from oil degradation depends on the presence of thermal and oxidative stressing agents that are in the system.

These include heat, water contamination, metal particles (metal catalysts) and air entrainment. Oil oxidation causes viscosity to increase from synthesis and polymerization of oil molecules.

A change in viscosity can result from a host of other root causes, such as the following:

- Excessive amounts of contamination, such as water, fuel, glycol and solvents
- Hydrolysis (from water contamination) of ester-based synthetic lubricants (lowers viscosity)
- Volatilization of the light ends of the base stock (increases the viscosity)
- Topping up with the incorrect viscosity grade
- Severe mechanical shearing of the oil (lowers viscosity)

Investigate the source of viscosity change by analyzing under- or over-limit viscosity according to the flow model described in Figure 5-8. As required, refer to the following tests as collateral information to determine the root cause of the problem:

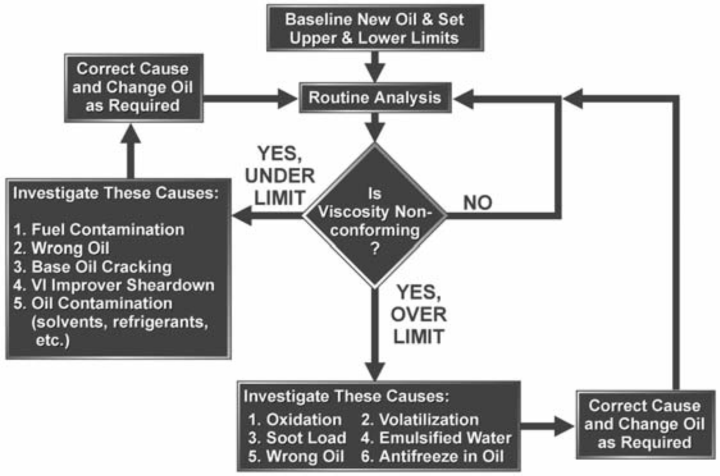

Baseline New Oil & Set Upper & Lower Limits
Correct Cause and Change Oil as Required
Routine Analysis
YES, UNDER LIMIT
Is Viscosity Non-conforming ?
NO
Investigate These Causes:
1. Fuel Contamination
2. Wrong Oil
3. Base Oil Cracking
4. VI Improver Sheardown
5. Oil Contamination (solvents, refrigerants, etc.)
YES, OVER LIMIT
Investigate These Causes:
1. Oxidation 2. Volatilization
3. Soot Load 4. Emulsified Water
5. Wrong Oil 6. Antifreeze in Oil
Correct Cause and Change Oil as Required

Figure 5-8 Viscosity Diagnostics

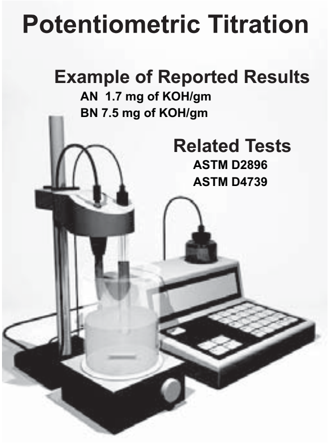


Figure 5-9 Potentiometric Titrometer Used to Determine the Acid Number

- Water content
- Flash point or fuel dilution tests
- Elemental spectroscopy (for contaminants like glycol, reactive metals, wrong oil)
- Oxidation stability
- Neutralization number for chemical degradation
- Infrared spectroscopy and other tests for oxidation, volatilization, chemical contamination, wrong oil and/or mechanical shearing

Applicable standards: ASTM D445, ISO 3105 and ISO 3448

5.2.3 Acid Number (AN). This method is primarily used for non-crankcase industrial lubricants. The acid number (AN) is a measure of the acid concentration of the oil. It does not measure acid strength (like pH). The AN is a titration test method, and results are expressed as the volume (milligrams) of potassium hydroxide (KOH) required to neutralize the acidic components in one gram of sample oil. The reported unit is mg KOH/gm of oil. AN can be quantified by either colorimetric (color change) or potentiometric (electrical voltage change) titration methods (see Figure 5-9). For dark-colored oils, use the latter method.

Some of the oil's additives (i.e., anti-rust and anti-wear additives) are slightly acidic and can produce a rather high initial AN value. Over time, this value can decrease as additives begin to deplete. As the oil ages and oxidizes, small amounts of organic acids begin to accumulate in the oil, causing the AN to increase. The amount of AN increase over and above the new oil's baseline is an indication of the degree to which the oil has degraded (or became contaminated by acids). A high AN typically indicates the oil's useful life has expired and it needs to be changed. For mineral oils and many synthetics, an AN above 4.0 is highly corrosive, risking attack of metal surfaces. Strong acids can enter an oil from contamination; these include sulfuric, nitric, hydrochloric, hydrofluoric and phosphoric. Corrosive damage risk is increased in the presence of water contamination, which strengthens the corrosive potential of acids.

A slow increase in AN over a long period of use is considered normal for certain lubricants. However, once an upper limit is reached, the oil will need to be changed. In other lubricants, any significant change in AN is reportable and may be a cause for concern. Rapid change in AN may be due to one or more of the following events:

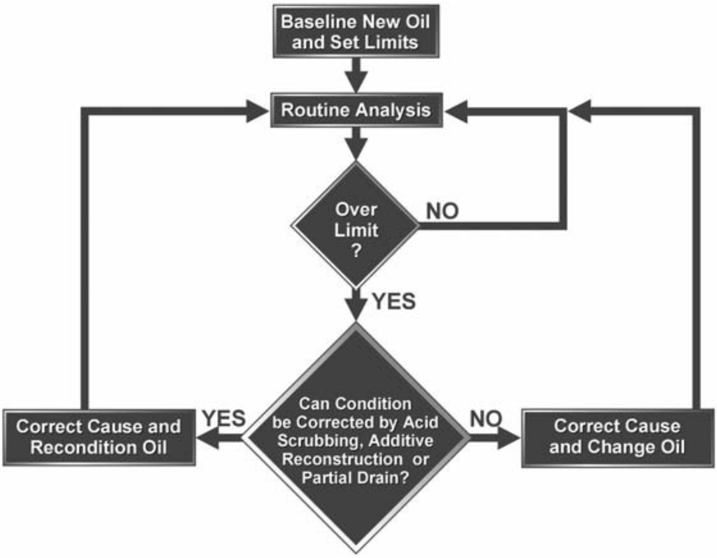

Baseline New Oil and Set Limits
Routine Analysis
Over Limit ?
NO
YES
Can Condition be Corrected by Acid Scrubbing, Additive Reconstruction or Partial Drain?
YES
NO
Correct Cause and Recondition Oil
Correct Cause and Change Oil

Figure 5-10 Acid Number Diagnostics

- Severe oxidation of oil
- Depletion of some additives (anti-wear, EP and rust-preventing)
- Large makeup of the incorrect oil such as anti-wear hydraulic oils or gear oils that have high baseline AN values

Diagnose AN numbers according to the flow model on Figure 5-10. Employ the following collateral test as required to determine the problem's root cause:

- Elemental spectroscopy
- Fourier transform infrared (FTIR) spectroscopy
- Moisture detection or quantification
- Viscosity
- Rotating pressure vessel oxidation test (RPVOT)
- Linear sweep voltametry

Applicable standards: ASTM D664, ASTM D974, ASTM D1534 (transformer oils) and ASTM D3339

5.2.4 Base Number (BN). Applied primarily to engine crankcase applications, the BN measures the reserve alkalinity of an oil. Engine oils are equipped with over-based additives (high alkalinity) that can neutralize the acids that are generated during combustion and enter the crankcase oil from blow-by. Once the reserve alkalinity is depleted through normal consumption as the oil ages, the oil can become highly corrosive.

Like the AN test, the BN test is performed by colorimetric or potentiometric titration (usually potentiometric due to the darkness of engine oil) (see Figure 5-9). But in the case of the BN, the alkaline oil is neutralized with hydrochloric (preferred for used oil analysis) or perchloric acid. Results are reported in mg KOH/gram of oil, same as the AN test, which can be confusing. The result is actually a derived value that represents the volume of KOH (potassium hydroxide) that is required to neutralize the volume of BN reagent acid (hydrochloric acid) that is required to neutralize the reserve alkalinity of the sample being tested. In this way, the units are synchronized (i.e., one unit of BN neutralizes one unit of AN).

BN numbers trend steadily downward as the oil's reserve alkalinity is depleted by acids from combustion and base oil oxidative. Rapid change in BN may be caused by one or more of the following:

- Burning high-sulfur fuel
- Abnormal fuel dilution
- Poor combustion
- Excessive blow-by
- Hot running conditions
- Severe oxidation
- Overextended drain interval
- Wrong oil addition
- Glycol contamination

Interpret BN numbers according to the flow model on Figure 5-11. If BN numbers change rapidly, determine the root cause and enact corrective actions.

Applicable standards: ASTM D974, ASTM D2896, ASTM D4739 and ASTM D5984-96

5.2.5 Fourier Transform Infrared (FTIR) Spectroscopy. FTIR is a method that provides a rapid means to monitor multiple oil parameters simultaneously. In one common instrument configuration, a fixed thickness of oil (path length) is applied to the FTIR instrument's test cell through which infrared energy is passed. Numerous oil properties, additives and contaminants absorb infrared energy at particular infrared spectral bands (similar to frequency). A Fast Fourier Transform (FFT) is applied to create a wavelength spectrum of attenuated (absorbed and reflected) infrared energy (ATR cell) or transmitted infrared energy (alternate method). The spectrum of the used oil is generally compared to the baseline of the new oil for

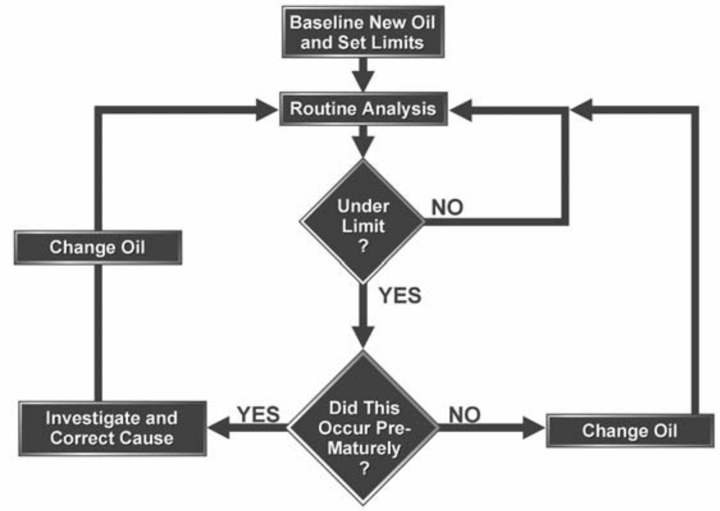

Baseline New Oil and Set Limits
Routine Analysis
Under Limit ?
NO
YES
Change Oil
Investigate and Correct Cause
YES
Did This Occur Pre-Maturely ?
NO
Change Oil

Figure 5-11 Base Number Diagnostics

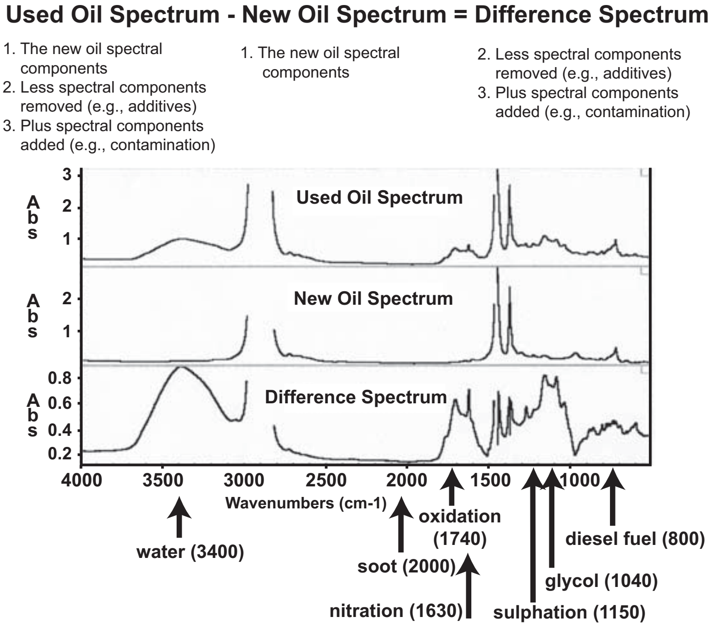


Figure 5-12 Spectral Subtraction Method for Infrared Spectroscopy

analysis to identify certain contaminants (e.g., soot, water, glycol and fuel), certain oil degradation products (e.g., oxides, nitrates and sulfates) and additives (e.g., zinc dialkyl dithiophosphate [ZDDP] and phenols) (see Figure 5-12).

Infrared spectroscopy is unique in that it assesses the constituent components of the oil sample at the molecular level. This information is very useful when the existence of compounds such as additives and oxidation by-products is of interest. Similar properties are difficult to derive by other means.

Oil contamination by water, soot, glycol, incorrect makeup oils and chemical solvents can all be monitored using FTIR. The analyst or instrument software looks for discrepancies in spectral features, or bands, at specific wavenumbers (WN) (see Figure 5-13). Soot produces a broadband spectrum shift, so a wavenumber where no other significant spectral activity occurs is selected for soot measurement (typically 2000 WNs). Wavenumbers refer to the number of spectral waves per centimeter of path length.

Parameter	Wavenumber (cm-1)
Oxidation	Mineral Oil - 1750 Organic Ester - 3540 Phosphate Ester - 815
Sulfation	1150
Nitration	1630
Soot	2000
Water	Mineral Oil - 3400 Organic Ester - 3625
Glycol	880, 3400, 1040 and 1080
Fuel	Diesel - 800 Gasoline - 750 Jet Fuel - 795 - 815
Phenol Inhibitors	3650
ZDDP Anti-wear/ Antioxidant	980

Figure 5-13 Common Spectral Search Areas Used in Infrared Spectroscopy

Overall lubricant health also can be monitored using FTIR. Oil degradation caused by oxidation and nitration results in unique wavenumber-specific absorption features (centering at 1750 and 1630 WNs, for instance). A decrease in absorption at spectral bands relating to certain additives also can be observed.

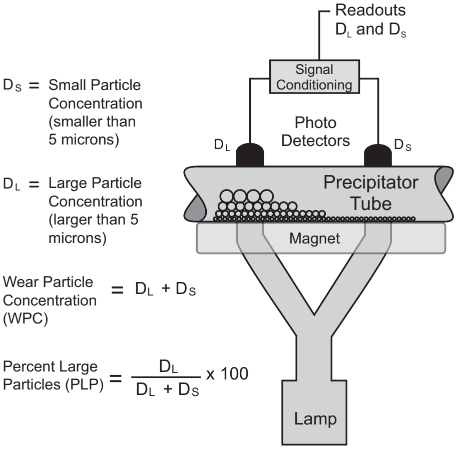

Readouts D_L and D_S
Signal Conditioning
Photo Detectors
D_L
D_S
Precipitator Tube
Magnet
Lamp
D_S = Small Particle Concentration (smaller than 5 microns)
D_L = Large Particle Concentration (larger than 5 microns)
Wear Particle Concentration (WPC) = $D_L + D_S$
Percent Large Particles (PLP) = $\frac{D_L}{D_L + D_S} \times 100$

Figure 5-14 Direct Reading Ferrography

For a number of reasons, many labs do not consider FTIR results to be sufficiently conclusive by themselves. However, when combined with other routine tests, FTIR can offer valuable supporting information relating to fluid properties and contamination.

Applicable standards: ASTM D7214-07a, ASTM D7412-09, ASTM D7414-09, ASTM D7415-09, ASTM D7416-09, ASTM D7418-07 and ASTM E2412-04

5.2.6 Ferrous Density. An increase in the population of large (greater than 5 microns) ferrous particles usually suggests the presence of an abnormal wear condition and should serve as a warning of impending failure. Several methods are available for determining the concentration of large ferrous debris. The severity of the wearing event is generally proportional to the increase in generation rate of large particles. The ferrous density instruments report results in different measurement units established by the instruments' manufacturer. These instruments are not currently standardized although widely used.

Contamination, poor lubrication and adverse mechanical conditions are the usual causes of high ferrous particles. Typically, at least one surface in a frictional pair is ferrous (iron or steel) and it is usually the surface most critical to machine reliability. For this reason, the monitoring of ferrous particle density in used lubricants can provide valuable machine health information. The need is further magnified by the fact that elemental analysis becomes less accurate with larger-size particles (greater than 5 microns), which is usually the critical size range in monitoring and detecting impending failure.

Ferrous density instruments use powerful rare-earth magnets to separate ferromagnetic particles from all other particles. Once these particles are separated, their density or concentration can be estimated using various means (optical, particle count method, magnetic flux method, etc.). It should be noted that some ferrous particles are generally not magnetic. These include corrosion debris (rust) and high-alloy stainless steel. Well-known commercial brands of ferrous density instruments include Particle Quantifier, Direct-Reading Ferrography, Ferrous Contam-Alert and CSI 51FW. Figure 5-14 shows the measurement units for direct reading ferrography, which is perhaps the ferrous density instrument most commonly used by commercial laboratories.

An increase in the generation of ferrous particles can be brought about by a number of factors, including:

- Load changes caused by increased production
- Eccentric loads caused by imbalance or misalignment

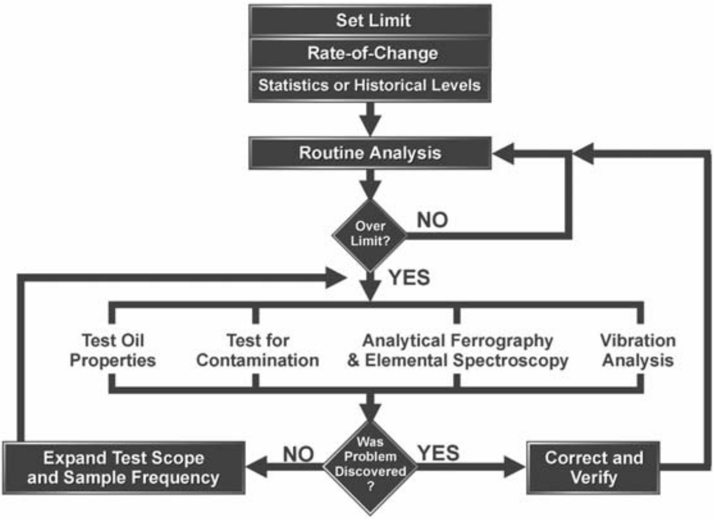


Figure 5-15 Ferrous density diagnostics

- Insufficient lubrication caused by the wrong lubricant, starvation, additive depletion or lubricant degradation

- Contamination by particles, water, air, coolant, fuel, solvents, etc.

- Component fatigue and wear

When abnormal wear is detected, apply the following diagnostic process (refer to the flow model in Figure 5-15):

- Localize the source of the debris with secondary sampling valves

- Assess the rate at which wear is being generated to determine severity

- Analyze the debris with analytical ferrography and elemental spectroscopy to determine the nature and severity of the problem (discussed later)

- Employ oil analysis, vibration analysis and other collateral information to determine the root cause

Applicable standards: Equipment supplier specific

5.2.7 Microscopic Contaminant and Wear Particle Identification. When abnormal wear metals have been identified by other methods (including particle counting, elemental spectroscopy and/or ferrous density analysis), a common and important exception test to perform next is microscopic particle examination and identification. The most common version of the procedure is referred to as analytical ferrography. Analytical ferrography involves the analysis of debris deposited onto a ferrogram slide (aided by a magnet) or alternatively a filtergram membrane (see Figure 5-16).

Using an optical microscope (typically with both bottom and top lighting), the particle morphology (shape), color, size, reflectivity, surface appearance, edge detail, angularity and relative concentration provides the analyst with clues about the nature, severity and root cause of the contaminant ingression or wear problem. Scanning Electron Microscopy (SEM) also can be used to examine particles as well as their elemental composition using an Energy Dispersive Spectroscopy (EDS) feature. Many ferrograms can be heated on a hot plate to 330° C to help

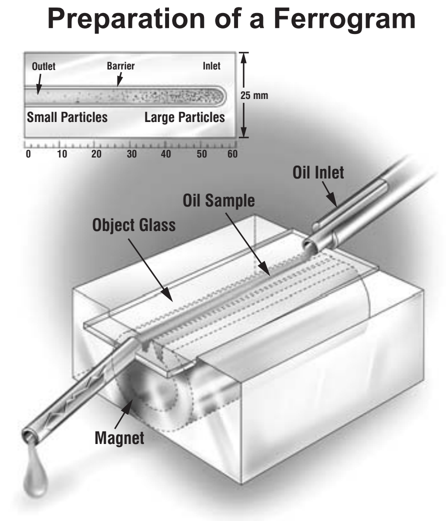


Figure 5-16 Particles are Pinned Down to the Ferrogram by a High-gradient Magnetic Field

reveal the composition of particles. The heat can alter the color of the particle to reveal its composition. The following describes how some particles change in color from heat exposure according to composition differences:

- Copper alloy: Yellow before and after heat treatment
- Aluminum alloy: Heat treat doesn't affect color
- Stainless steel: Slight straw color when heated
- Lead/tin Babbitt: White color, mottled blue, purple when heated
- Copper/lead Babbitt: Yellow color; becomes yellow with blue/purple mottling when heated
- Low-alloy steel (exposed to progressive heating): light tan >> straw color >> blue/violet >> pale blue

Although largely a qualitative technique, the analyst typically reports the presence and concentration of wear particles, friction polymers, dirt and sand, fibers, and other solid contaminants on a 1-to-10 or 1-to-100 scale to communicate severity or concentration of the debris field. Descriptive text and photomicrographs usually accompany the enumerated values to clarify conclusions and recommend corrective actions.

It is important to determine the root cause of machine failure and abnormal wear problems so they can be eliminated and to help you avoid recurrence. By combining information from analytical ferrography with other lubricant analysis and maintenance technology evaluations, the analyst attempts to answer the following questions:

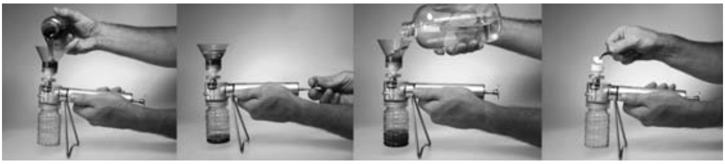
- Where in the machine does the contaminant or wear debris originate?
- What is causing it?
- How severe or threatening is it (residual life)?
- Can the condition be mitigated or arrested without downtime or loss production?

Applicable standards: none

5.2.8 Patch Test. This method is similar to microscopic contaminant and wear particle identification (previously described). A small amount of sample is pulled using a vacuum pump (either manual or electric) through a porous membrane (typically around 5 microns) to enable suspended particles to become deposited onto the membrane's surface. A solvent is used to rinse any residual oil from the surface of the membrane. Afterward, the membrane can be visually inspected for overall particle density and color. If an abnormal debris field is encountered, the membrane can be placed under a top-lit microscope for detailed analysis and characterization of the particles (see Figure 5-17 a, b & c).

Many analysts estimate the fluid's ISO Code (ISO 4406:99) based on overall appearance of particles, sometimes using comparator standards. One such comparator standard used in patch analysis of aviation fuels is discussed in Appendix A3 of ASTM D2276 and is easily adapted to lubricants and hydraulic fluids. However, unlike optical particle counters, patch testing allows particle shape, color, edge detail and organic particles to be inspected. And, unlike analytical ferrography, patch testing is relatively inexpensive and can easily be performed in the field.

Applicable standards: ASTM D2276 (fuel) and SAE ARP 4285



1. Introduce sample with solvent into patchmaking funnel

2. Pull vacuum to transfer fluid through patch

3. Rinse with solve

4. Remove patch for inspection

Figure 5-17a Patch Preparation Sequence

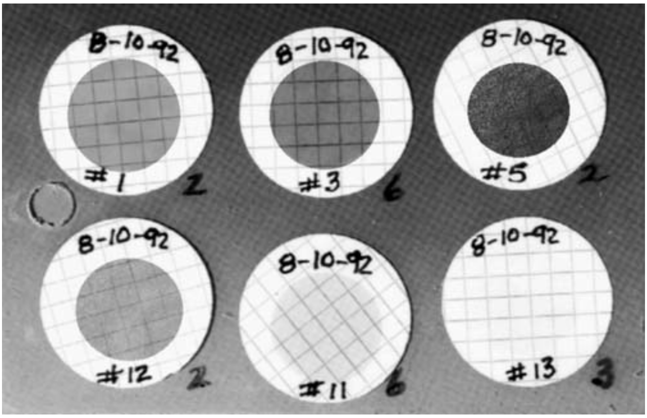


Figure 5-17b Patches of Insoluble Residue

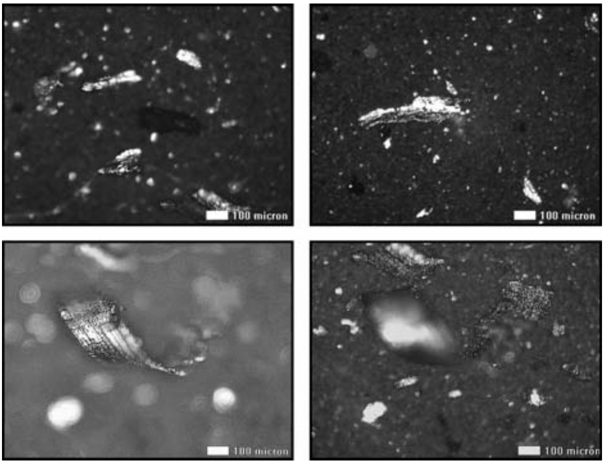


Figure 5-17c Patch Images Under Magnification

5.2.8 Rotating Pressure Vessel Oxidation Test (RPVOT). This test method (also known as the rotating bomb oxidation test) utilizes an oxygen-pressured vessel (bomb) to evaluate the oxidation stability of the sample oil at high temperatures in the presence of water and a copper catalyst coil. The vessel is charged with oxygen to a pressure of 620 kPa (90 psi), placed in a constant-temperature oil bath at 150° C, and rotated axially at 100 rpm at an angle of 30 degrees. The number of minutes required to reach a specific drop in gauge pressure for a used oil is compared to the reference number of minutes required for a new oil. A significant change between the new and used oil relates to a change in an oil's oxidation stability and remaining useful life (RUL).

Oxidation begins (aided by heat, water and metal catalysts) with the formation of chemically unstable compounds (e.g., free radicals ands hydroperoxides) from the oil's hydrocarbon molecules. These compounds are then easily oxidized, thereby initiating a chain reaction that consumes an increasing volume of the base oil molecules. The final products of oxidation are corrosive acids as well as resins and sludge that accumulate in piping, coolers, filters, component oil ways, valves (causing sticking) and the oil reservoir. In addition, oxidation will increase the oil's viscosity, which inhibits oil flow and potentially leads to lubricant starvation.

A gradual loss of the oxidation stability over a long period of service is considered to be normal; however, it should not be allowed to progress too far. The RPVOT test is more expensive and time consuming than most used oil analysis tests. Therefore, its application is generally limited to machines that hold large volumes of lubricant, such as some hydraulic systems, turbine oil applications and compressors. The use of the RPVOT is particularly beneficial when outages (shutdowns) are infrequent and there is a need to forecast the service life of a lubricant and its ability to reach the next planned outage event.

The rate of oil oxidation can increase rapidly in the presence of the following conditions:

- Decreased capability of the oil to resist oxidation due to antioxidant additive depletion or removal

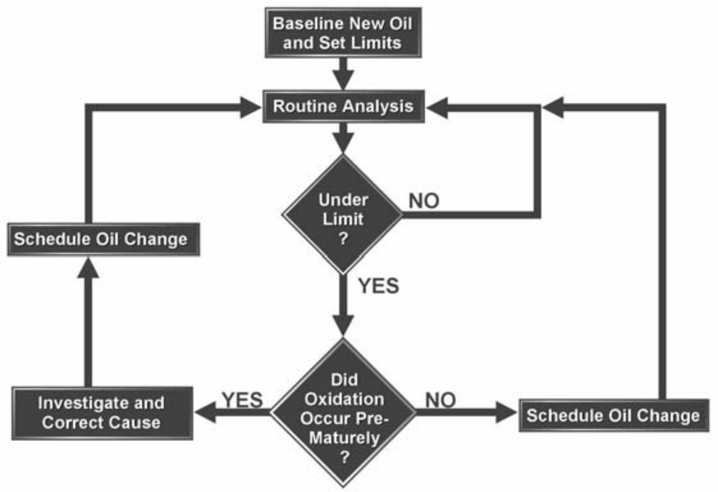

Baseline New Oil and Set Limits
Routine Analysis
Under Limit ?
NO
YES
Schedule Oil Change
Did Oxidation Occur Pre-Maturely ?
YES
NO
Investigate and Correct Cause
Schedule Oil Change

Figure 5-18 RPVOT Diagnostics

- Increased oil or machine surface temperatures
- Contaminants such as metal particles and nascent metal surfaces that act as oxidation catalysts
- Increased levels of entrained air
- Increased presence of water (especially dissolved and emulsified water)
- Increase in oil pressure
- Increase in oil agitation

Diagnose RPVOT data according to the flow model in Figure 5-18. If the oxidative life is normal or in a safe range, no additional testing or action is required. If the RUL is abnormal (short), consider the following corrective actions:

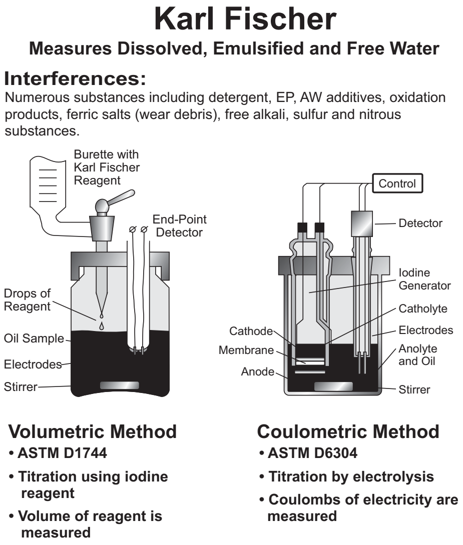
- Reduce oxidative stress (heat, air, water and reactive metals)
- Upgrade base oil quality
- Upgrade the oil's antioxidant additive package (confirm effectiveness by laboratory testing first)
- Change the oil or do a partial drain and fill (a.k.a. bleed and feed)

Always investigate stressing conditions if RUL decays in an exceedingly short space of time.

Applicable standard: ASTM D2272

5.2.9 Water Content by Karl Fischer. The Karl Fischer test is a titration method to measure water in oil. It is usually performed after the sample is screened with the hot plate "crackle test" or by FTIR as a cost-saving measure. Karl Fischer reports water content as concentration in percentage or parts per million (ppm) of the "total" water (free, emulsified and dissolved) in the oil sample. One percent water equals 10,000 ppm.

In the volumetric test (see Figure 5-19), the oil is titrated with a standard iodine containing Fischer reagent to an electrometric end point. The accuracy of the test is affected by the presence of sulfur-containing additives such as detergents, anti-wear agents, rust inhibitors and EP anti-scuffing agents. Many labs prefer the coulometric method (Figure 5-19) combined with co-distillation to eliminate the risk of additive interferences.



Karl Fischer

Measures Dissolved, Emulsified and Free Water

Interferences:

Numerous substances including detergent, EP, AW additives, oxidation products, ferric salts (wear debris), free alkali, sulfur and nitrous substances.

Volumetric Method

- **ASTM D1744**
- **Titration using iodine reagent**
- **Volume of reagent is measured**

Coulometric Method

- **ASTM D6304**
- **Titration by electrolysis**
- **Coulombs of electricity are measured**

Figure 5-19 Karl Fischer Test Method for the Measurement of Water in Oil

Water rusts iron and steel surfaces, accelerates corrosion, depletes and degrades additives, promotes base oil oxidation, and reduces lubricant effectiveness. Large amounts of water form persistent emulsions that join with insoluble oxidation products to form a sludge and may significantly impair machine reliability. In addition, free water may cause the formation of hard, brittle deposits on bearing surfaces and promote bacteria growth.

Look for the following causes of increased water content:

- Topping up with water-contaminated fluid
- Ineffective operation of a vapor extraction system
- Leaking oil coolers
- Excessive leakage from turbine gland steam seals
- Washdown sprays and leaky hatches
- Atmospheric condensation in the reservoir

When water is detected, diagnose the aberrant condition according to the flow model in Figure 5-21, and identify and eliminate the source of the water ingress.

- If high water content is caused by accidental contamination (with new oil), review the existing makeup procedure to avoid similar problems in the future.
- Ensure that there are no air leaks bypassing the reservoir's cover seals and that the vapor extraction fans are operating properly. With regard to the fans, too low of a vacuum can cause a buildup of humidity, whereas too high of a vacuum can pull in more gland steam or cause oil carryover.
- Check the oil coolers for leaks. To detect cooler leaks, the cooling water discharge at the coolers also should be checked for traces of the oil. Also, review the inventory control (i.e., make-up) to determine if the oil use has been higher than normal. If the leak can't be detected, charge the system with pressure in isolated segments and look for a pressure drop to indicate the leaking area.

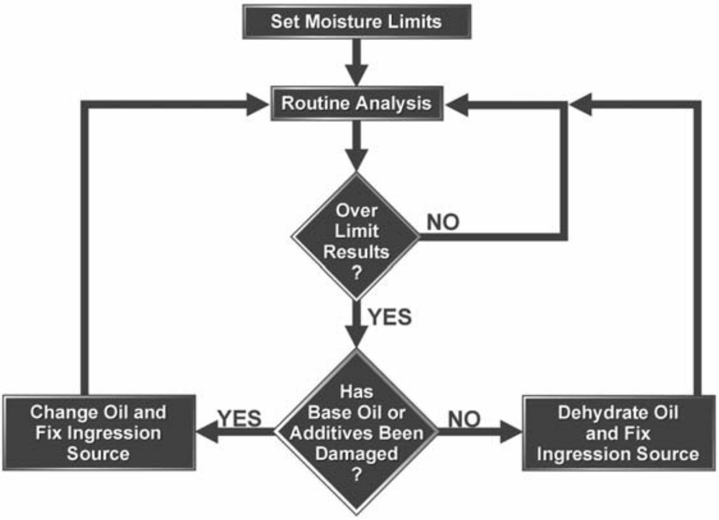

Set Moisture Limits
Routine Analysis
Over Limit Results ?
NO
YES
Has Base Oil or Additives Been Damaged ?
YES
NO
Change Oil and Fix Ingression Source
Dehydrate Oil and Fix Ingression Source

Figure 5-21 Water Contamination Diagnostics

- If the turbine gland steam seals are suspected as the source of the water ingress, check the gland inlet and outlet pressure and regulate as required where gland conditions permit. In addition, consider inspecting the glands during the next outage.

Applicable Karl Fischer standards: ASTM D1744-volumentric (withdrawn but still in active use) and ASTM D6304-98-coulometric

5.2.10 Elemental Spectroscopy. Elemental spectroscopy quantifies the presence of dissolved and some undissolved inorganic materials by element in the oil. Nearly all elemental spectrometers used today for oil analysis are the atomic emission type. These instruments work by exposing the sample to extreme temperatures generated by an arcing electrode commonly referred to as a rotating disc electrode (RDE).

Another common method uses an argon plasma torch to vaporize the sample. This is known as an inductive coupled plasma spectrometer (ICP). Refer to Figure 5-22 for the basic anatomy of these two common types of spectrometers. The extreme heat excites the atoms in the sample, causing them to emit energy in the form of light. Each atomic element emits light at a specific frequency. The spectrometer

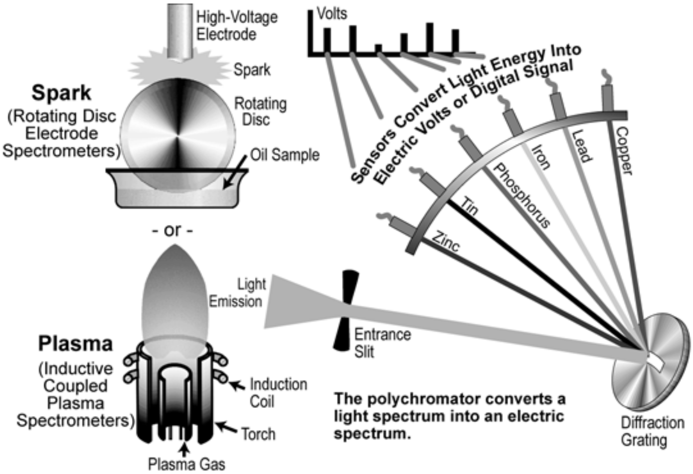

High-Voltage Electrode
Spark
Spark (Rotating Disc Electrode Spectrometers)
Rotating Disc
Oil Sample
- or -
Light Emission
Plasma (Inductive Coupled Plasma Spectrometers)
Induction Coil
Torch
Plasma Gas
Volts
Sensors Convert Light Energy Into Electric Volts or Digital Signal
Copper
Lead
Iron
Phosphorus
Tin
Zinc
Entrance Slit
The polychromator converts a light spectrum into an electric spectrum.
Diffraction Grating

Figure 5-22 Emission Spectrometer Anatomy

quantifies the amount of light generated at these frequencies, which is mathematically translated into concentration of each element (iron, lead, tin, etc.) in parts per million (ppm) or parts per billion (ppb).

Most elemental spectrometers report the concentration of 15 or more elements. The elements reported can provide an indication of increased generation of wear, ingress of contamination or depletion of certain additive elements.

Atomic emission spectroscopy (AES) is particle-size limited. Dissolved metals and suspended particles up to approximately 2 microns are detected with high accuracy. The accuracy diminishes as particle size increases up to 5 microns. Elemental concentrations can be greatly understated for particles larger than 5 microns.

A less-common alternative method is X-ray Fluorescence Spectroscopy (XRF), which is not particle-size limited like conventional AES spectrometers. SRF also doesn't require the sample to be in a liquid form and is often used with grease, sludge, filter debris, magnetic plug debris, etc. However, these instruments are hampered by the fact that they're lower limit of sensitivity ranges higher than ICP and RDE technologies. In other words, they can't measure and report low concentrations of calcium, chromium and copper when compared to ICP and RDE. This is a non-standardized method in lubrication applications.

Increasing or decreasing elemental concentration can signal a change in the generation of wear debris, the ingress of contaminants and the addition or depletion of additives. The information in Figure 5-23 generally categorizes the common elements observed with oil analysis as wear, contamination or additives. Figure 5-24 shows common concentration ranges of wear metals in different types of machines.

Element	Wear	Contamination	Additive
Iron (Fe)	X	X	
Copper (Cu)	X	X	X
Chromium (Cr)	X		
Tin (Sn)	X		
Aluminum (Al)	X	X	
Lead (Pb)	X		
Silicon (Si)		X	X
Sodium (Na)		X	X
Boron (B)		X	X
Calcium (Ca)		X	X
Magnesium (Mg)		X	X
Zinc (Zn)	X		X
Phosphorous (P)		X	X
Molybdenum (Mo)			X
Potassium (K)		X	

Figure 5-23 Common Elements and Their Sources

	Fe	Cr	Al	Pb	Cu	Si
Diesel Engine	3-150	0-20	2-20	3-50	5-65*	1-15
Gasoline Engine	25-300	2-25	2-40	10-75	10-80*	1-15
2-Cycle Natural Gas Engine	1-40	0-4	0-10	0-20	2-30	0-9
4-Cycle Natural Gas Engine	5-80	0-19	1-20	3-40	3-50*	1-15
Off-Highway Hydraulics	1-20	0-9	1-10	1-15	2-20	1-15
Final Drive	25-300	0-9	1-10	10-75	10-200	5-45
Differential	50-600	2-20	1-40	10-100	15-250	5-65
Auto-Powershift Transmission	10-100	0-10	3-50	10-350	10-350	5-90
Manual Transmission	30-400	2-15	1-40	10-75	15-100	5-50
Rotary Screw Component	3-30	0-4	0-4	0-20	3-39	0-14**
Centrifugal Air Cond.	0-20	0-1	0-1	0-40	0-30	0-3
Gas Turbine	0-20	0-4	0-3	0-3	0-15	0-5
Industrial Gearing	3-150	0-4	1-20	3-40	10-80	5-65
Industrial Hydraulic	0-10	0-1	0-2	0-10	0-10	0-10

Fe = Iron Cr = Chromium Al = Aluminum Pb = Lead Cu = Copper Si = Silicon

Figure 5-24 Common Elemental Concentration Ranges for Different Types of Machines

Consider the following discussion when diagnosing non-conforming elemental data:

- An increase in the concentration of such elements as iron, copper, chromium, tin, aluminum and leads suggest that abnormal wear is occurring. Further steps should include analysis of the debris with complementary testing to determine its severity, nature, origin and root cause (see Figure 5-25).
- Increasing concentration of silicon, sodium, boron, calcium and magnesium can signal the ingress of contamination. A lock-step increase in silicon and aluminum typically suggests dirt ingress, although silicon also is the primary element found in anti-foaming additives (silicone), which can cause confusing results. Increasing levels of sodium and boron may signal the ingestion of glycol-based coolant (see Figure 5-26). Calcium and magnesium are often present when hard water is ingested due to spraydowns or cooling system leaks, but they also are common elements found in engine oil additives.
- Numerous elements are used in a multitude of additives. For instance, zinc and phosphorous are common in anti-wear additives; sulfur, phosphorous and molybdenum are common components of extreme-pressure additives; and calcium and magnesium are frequently components of engine oil alkalinity improvers. Knowledge of the new oil baseline is critical to trending additive depletion with elemental spectroscopy (see Figure 5-27).

Applicable standards: ASTM D4951 (ICP, additives), ASTM D5185 (ICP, additives, wear metals and contaminants), ASTM D6595 (RDE, additives, wear metals and contaminants), and ASTM D7303-06 (metals in grease by ICP)

5.2.11 Flash Point Test and Fuel Dilution Instruments. The flash point, when used to analyze used oils, can identify the presence of volatile molecules from fuel and other flammable contaminants. A lubricant's flash point is the lowest temperature at which an ignition source (small flame) applied to the oil's surface causes the vapors of the lubricant to ignite under specified conditions. The oil is said to have

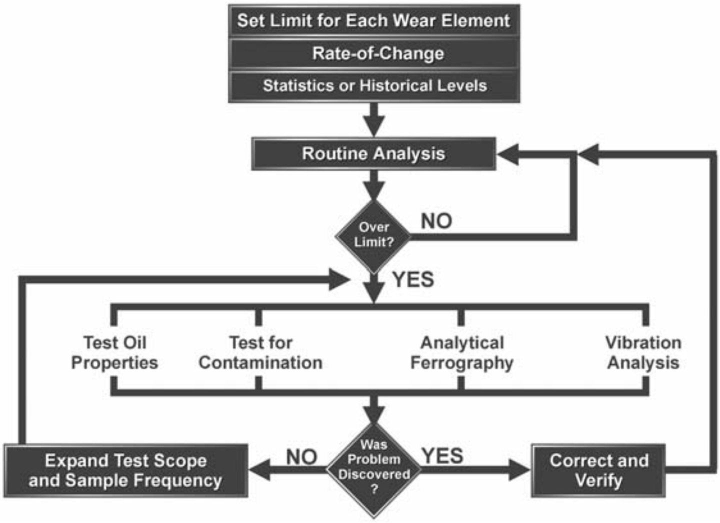


Figure 5-25 Elemental Wear Metal Diagnostics

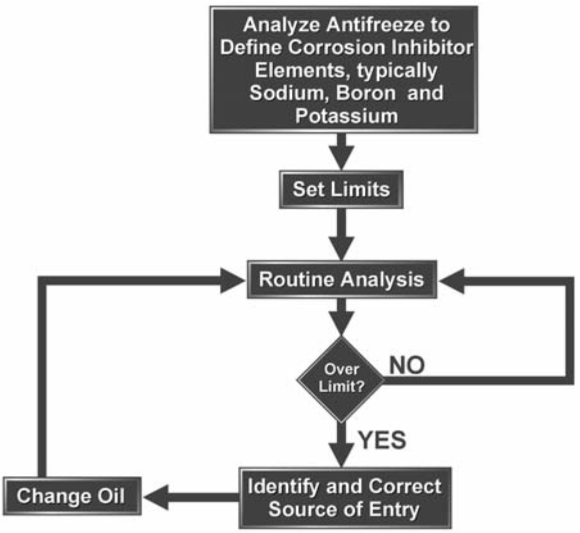

Analyze Antifreeze to Define Corrosion Inhibitor Elements, typically Sodium, Boron and Potassium
Set Limits
Routine Analysis
Over Limit?
NO
YES
Identify and Correct Source of Entry
Change Oil

Figure 5-26 Diagnostics of Common Additive Elements from Glycol Contamination

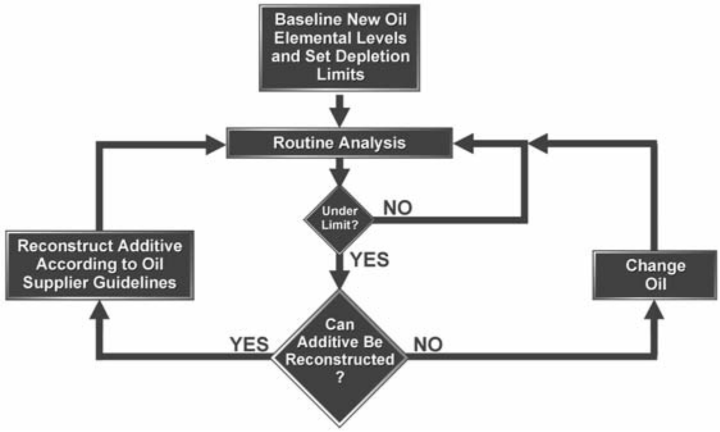

Baseline New Oil Elemental Levels and Set Depletion Limits
Routine Analysis
Under Limit?
NO
YES
Reconstruct Additive According to Oil Supplier Guidelines
Change Oil
Can Additive Be Reconstructed ?
YES
NO

Figure 5-27 Additive Depletion Diagnostics Using Elemental Analysis

"flashed" when a blue flame appears and instantaneously propagates itself over the entire surface. The oil flashes because a flammable mixture results when it is heated sufficiently, causing vapors to emerge and mix with oxygen in the air. The flash point temperature of an oil corresponds roughly to a vapor pressure of 3 to 5 millimeters of mercury (Hg). Figure 5-28 shows the contaminants and other influencing conditions that can alter the flash point in used oils.

Many laboratories simply test up to a specified temperature, say 20° C below the oil's normal flash point. If the oil flashes at this lower temperature, it can be reliably assumed that it has been diluted with fuel or another low-boiling-point flammable liquid. This pass/fail use of the flash point test reduces the time to perform the test as well as its cost. Those oils that fail can then be analyzed further to determine the specific flash point to estimate the total contaminant level (fuel contamination, for instance).

This test is commonly used with engine oils (diesel, gasoline and natural gas) and occasionally with natural gas compressor lubricants to detect excessive gas solubility. The closed-cup flash point test is the most widely used method for fuel dilution testing due to its sensitivity to low concentrations of fuel (see Figure 5-29). Fuel or chemical dilution severely impairs the lubricant's effectiveness and can cause fire or explosion hazard. Refer to Figure 5-29 in evaluating fuel dilution data.

	Decreases Flash Point	Increases Flash Point
Changes in Oil Chemistry:	- Thermal Cracking - Radiation (cracking by gamma rays) - Microdieseling	- Polymerization
Additions to the Oil:	- Diesel Fuel - Gasoline - Natural Gas - Solvents - Wrong Makeup Oil - Water (instrument interference)	- Water - Coal Dust - Glycol / Antifreeze - Wrong Makeup Oil
Subtractions from the Oil:		-Thermal Evaporation (boiling off of light ends) - Vacuum Dehydration

Figure 5-28 Contaminants and Conditions that Alter an Oil's Flash Point

Flash Point Test	Flash Limits		Applications	Standards
	°F	°C		
Cleveland Open Cup	Over 175	Over 79	Lubricants and hydraulic fluids, not fuel oils. Requires about 100 ml. Determines flash temperature in about 30 minutes	ASTM D 92 ISO 2592 IP 36 DIN/EN 22592
Pensky-Martens Closed Cup	104 – 680	40 - 360	Lubricants, hydraulic fluids, fuel oils and other liquids with viscosities above 5.5 cSt at 40°C. Requires 75 ml of fluids.	ASTM D 93 IP 34/88 ISO 2719 DIN/EN 22719
Small-Scale Closed Cup - Method A: Flash / No Flash - Method B: Finite Flash Point	104 – 572	40 – 300	Lubricants, hydraulic fluids and fuel oils. Method A is a pass / fail test for preset flash temperatures. Requires 2-4 ml of fluid. Test time about 1-2 minutes. Method B takes longer test time and more fluid.	ASTM D 3828-97 IP 303/83 (88) ISO 3679

Figure 5-29 Summary of Flash Point Tests Relating to Lubricating Oils

Applicable Flash Point standards: ASTM D92 (Cleveland open cup), ASTM D93 (Pensky-Marten closed cup) and ASTM D3828-97 (small-scale closed cup)

5.2.12 Other Used Oil Analysis Tests. The previously described tests represent the core analytical methods used in the analysis of in-service lubricating oils. There are many instruments and methods that are emerging onto the market that show considerable promise. Likewise, there are others that serve niche applications and still others that are slowly being phased out to make room for new technology. It is not possible to discuss all of these technologies and analytical methods. However, there are a few that fall outside of the mainstream that, for various reasons, are worth noting:

Ultracentrifuge. Some labs utilize a sedimentation rating system employing the use of an ultracentrifuge. Ultracentrifugation allows estimation of total insolubles as an indication of varnish potential (oxide insolubles, carbonaceous resin, additive precipitants, etc.). A small amount of sample is placed in a special plastic test tube without solvent dilution. The tube is placed in an ultracentrifuge for 30 minutes at 20,000 rpm. The test subjects the oil to gravitational forces reaching 34,800 Gs. The force effectively extracts the sludge and varnish precursors, driving them to the bottom of the tube. The density of the concentrated material is then compared to a visual sediment-rating scale. This is a non-standardized method.

Membrane Patch Colorimetry. This method uses a petroleum ether and a 0.45-micron patch to coagulate and extract insolubles from an oil for the purpose of estimating varnish potential. The insolubles deposited on the surface of the membrane are inspected optically for color and density. Optionally, a gravimetric of the membrane can be performed to quantify insoluble concentration. As of this writing (June 2010), this method is currently being reviewed as a possible ASTM standard.

Dielectric Measurements. Various dielectric measurement instruments have emerged on the market over the years for assessing contaminants and chemical properties of lubricants. These include online sensors, portable instruments and bench-level instruments.

One such instrument is described in ASTM D7416-09 and uses a time-resolved dielectric permittivity method to identify the onset of oil oxidation, moisture contamination and changes in oil chemistry.

Optical Soot Meters. While some labs commonly use infrared spectroscopy to estimate the percentage of soot in engine oil (described previously), other labs prefer to use single-channel optical devices (either white light or infrared) to quantify the amount of non-transmitted light through a fixed path length or by using an ATR (attenuated total reflectance) cell. The non-transmitted light fraction is defined as the soot load of the oil and is often reported as percent soot. This is a non-standardized test method.

Blotter Spot Testing. This simple test, also known as paper chromatography or radial planar chromatography, is used to examine soft insoluble suspensions in oil using blotter paper to which a small aliquot of sample is applied. Varnish and sludge-producing impurities will form distinct deposits and rings on the blotter paper as the oil wicks outward in a radial direction by capillary action. These impurities include carbon insolubles, oxide insolubles, additive degradation products and glycol contamination. This is a good field and laboratory test and is non-standardized.

Calcium Hydride Moisture Testers. One of the simplest and most convenient ways to determine water concentrations in the field is by using a calcium hydride test kit. This method employs the known reaction of water with solid calcium hydride to produce hydrogen gas. Because the reaction occurs stoiciometrically, the amount of hydrogen gas liberated is directly proportional to the amount of water present in the sample. Therefore, the water content of the sample can be determined by measuring the rise in pressure in a sealed container due to the liberation of hydrogen gas as any water in the sample reacts with the calcium hydride. Used correctly, these test kits are reported to be accurate down to 50 ppm free or emulsified water. This is a non-standardized method.

Glycol Reagent Method. The Schiff's reagent method (ASTM D2982) is a colorimetric method for detecting trace amounts of glycol in lubricating oils. In this method, a solution of hydrochloric

(HCl) acid and periodic (HIO3) acid is introduced to the oil to oxidize any glycol that may be present. The reaction produces an aldehyde, which in turn reacts with the Schiff's reagent, yielding a positive color change from colorless to pink/purple – the darker the color, the more glycol present.

Crackle Test. The crackle test is a non-instrument method of determining the presence of water in oil and, in some instances, estimating its concentration. The usual procedure is to place a couple drops of oil on the surface of a hot plate (320° F) and then visually examine the response of the oil to the heat. Oil with no free or emulsified water will become thin and spread due to the heat. Free and emulsified water will result is vapor bubbles and scintillation (crackling sound). With practice, the concentration of water can be estimated when compared to known levels of water. This is a non-standardized method.

Fuel Dilution Meter. One other instrument of note is the Fuel Dilution Meter (formerly branded the Fuel Sniffer), which uses surface acoustic wave (SAW) technology to detect and quantify fuel contamination in motor oil. Based on Henry's Law, it samples the "headspace" in a bottle of oil to assess fuel vapor concentration. Fuel vapor concentration correlates to fuel dilution in the oil. This is a non-standardized method.

Linear Sweep Voltametry (LSV). In many applications, it is of real value to monitor the progressive depletion of individual antioxidants to estimate the RUL. Antioxidants are the first component of many oil formulations to be impacted by thermal and mechanical stress; hence, there is a need to provide early warning for incipient lubricant failure. LSV applies a variable voltage to the sample while measuring the current flow. The presence and concentration of various antioxidant additives (specifically phenols, amines and ZDDP) can be determined based on their unique electrochemical oxidation potential and the magnitude of the induced current. Applicable standards: ASTM D6971 (amines) and ASTM D6810 (phenols).

Pressure Differential Scanning Calorimetry (PDSC). This test (ASTM D6186) is somewhat similar to the RPVOT and LSV methods. It produces information on an oil's oxidation stability and is preferred by some laboratories. PDSC works by placing a sample into a test cell. The cell is heated and pressurized with oxygen. When the sample starts to oxidize, an exothermic reaction occurs, which liberates heat. By measuring the onset of the reaction in the used oil (commonly called the induction point) in reference to the new oil, an estimate of the oxidation stability of the lubricant can be made.

5.3 Selecting the Test Slate

It is important that the oil analysis test slate include those tests that provide meaningful information for a specific piece of equipment. Some tests are routine in nature while others are exceptional tests, triggered by the abnormal level of a routine test. Figure 5-30 describes the appropriate routine and exception test slate for typical machine types.

Selecting Oil Analysis Tests By Application

Test or Procedure	Paper Machine Oils	Motor & Pump Bearings	Diesel & Gas Engine	Hydraulics	Air & Gas Compressors	Chillers and Refrigeration	Transmissions, Final Drives, Differentials	Industrial Gear Oils	Steam Turbine Oils	Gas Turbine Oils	EHC Fluids***
1. Particle Count	R	R	R	R	R	R	R	R	R	R	R
2. Viscosity											
a. 40°C	R	R	-	R	R	R	R	R	R	R	R
b. 100°C	-	-	R	-	-	-	-	-	-	-	-
3. AN	R	E(5a)	-	R	R	R	R	R	R	R	R
4. BN	-	-	R	-	-	-	-	-	-	-	-
5. FTIR											
a. Ox/Nit/Sul	R	R	R	R	R	R	R	R	R	R	-
b. Hindered Phen	-	R	-	R	R	-	-	R	R	-	-
c. ZDDP	-	R	-	R	R	-	R	R	-	-	-
d. Fuel Dil/Soot	-	-	R	-	-	-	-	-	-	-	-
6. Flash Point	-	-	R	-	R*	-	-	-	-	E(2b,5d)	-
7. Glycol-ASTM Test	-	-	E(14b)	-	-	-	-	-	-	-	-
8. Ferrous Density	E(1)	E(1)	R	R	R	R	R	R	E(1)	E(1)	R
9. Analytical Ferrography	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)
10. RPVOT	-	-	-	-	R	-	-	-	R	R	-
11. Crackle	R	R	R	R	R**	R	R	R	R	-	R
12. Water by KF	E(11)	E(11)	E(11)	E(11)	E(11)**	E(11)	E(11)	E(11)	E(11)	-	E(11)
13. Water Separability	R	-	-	-	R**	-	-	-	R	-	-
14. Elemental Analysis											
a. Wear Metals	R,E(1)	R,E(1)	R	R,E(1)	R,E(1)	R,E(1)	R	R,E(1)	R,E(1)	R	R,E(1)
b. K, Na, B, Si	R	R	R	R	R	R	R	R	R	R	R
c. Additives	R	R	R	R	R	R	R	R	R	R	R

*Gas Compressors Only **Air Compressors Only ***For phosphate ester fluids, consult fluid supplier and/or turbine manufacturer

R = Routine Testing
E = Exception test keyed to a positive result from the test in parenthesis

Figure 5-30 Commonly Used Routine and Exception Tests in Oil Analysis

6. Targets, Limits, Diagnostics and Data Management

6.1 Setting Limits and Targets

Historically, users of oil analysis have relied almost exclusively on commercial oil analysis laboratories or oil suppliers to identify when a machine is in alarm. Realizing the limitations of this approach, world-class organizations are taking charge of their own alarm settings to ensure that their specific objectives are met. The advent of sophisticated oil analysis software has put this objective within reach of most anyone who desires it.

The primary purpose for alarms or limits is to filter (funnel) data so that the technologist spends his time managing and correcting exceptional situations instead of laboriously perusing the data trying to find the exceptions. The alarm serves as a "trip-wire" to tell the analyst that a threshold has been passed and that action is required. Some data parameters have only upper limits such as particle counts or wear debris levels. A few data parameters employ lower limits like BN, additive elements, flash point, oxidation stability and FTIR (additive). Other data parameters like viscosity and FTIR use both upper and lower limits. These generally relate to important chemical and physical properties of the lubricant where stability of these properties is desired (not too much, not too little) (see Figure 6-1).

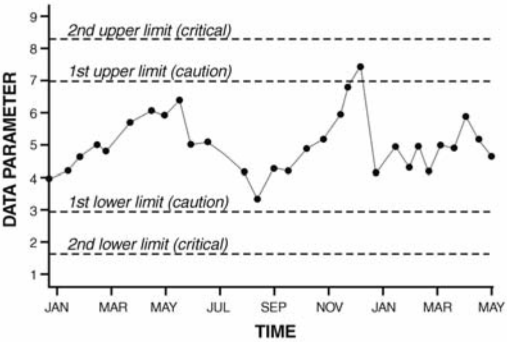


Figure 6-1 Example of Use of Upper and Lower Limits on a Given Oil Analysis Parameter

Alarming techniques vary to fulfill the requirements of different oil analysis objectives. These techniques can be generally categorized as follows:

Proactive Alarms – Proactive alarms alert the user to abnormal conditions associated with controlling the root causes of machine wear, operating faults and lubricant degradation. They are keyed to the proactive maintenance philosophy of setting targets and stabilizing lubricant conditions within those targets. A strategic premise of proactive alarms is that they be set to levels that will generate improvement over past performance (e.g., cleaner, dryer, cooler, etc.) or ensure that conditions are maintained to within levels that have previously been optimized relative to organizational objectives. Within the proactive domain, we utilize the following types of alarms and limits.

- ○ **Goal-based Targets** – Targets apply to the control of parameters like contamination to achieve machine life extension (see Figure 6-2). For example, a hydraulic machine running at ISO 18/15/12 cleanliness will experience a three-times life extension if the fluid is cleaned to an ISO 15/12/9 cleanliness. Setting the limit at ISO 15/12/9 is a goal-based initiative. Conversely, if the same hydraulic machine is running at ISO 15/12/9 and control is lost, allowing the contamination level to reach ISO 18/15/12, we can expect a three-times increase in wear during that period. The desire to return the system to an ISO 15/12/9 is driven by a specific objective and is, therefore, a goal-based limit. This type of limit is usually applied to particle count, moisture level, glycol level, fuel dilution, AN and other common root cause conditions.

- ○ **Aging Limits** – Another type of proactive limit or alarm relates to the progressive aging of a lubricant or hydraulic fluid (see Figure 6-3). From the moment a fluid is placed in service, its chemical and physical properties transition away from the ideal (i.e., those of the new formulated oil). Some properties transition very slowly, while others transition very dynamically. Limits keyed to the symptoms of lubricant deterioration are referred to as aging limits. Aging limits can be effectively applied to such parameters as AN/BN, viscosity, RPVOT, LSV, PDSC, elemental spectroscopy for additives, and FTIR (oxidation, nitration, sulphation and additives) and dielectric properties. Figure 6-4 shows some example limits for both goal-based and aging parameters.

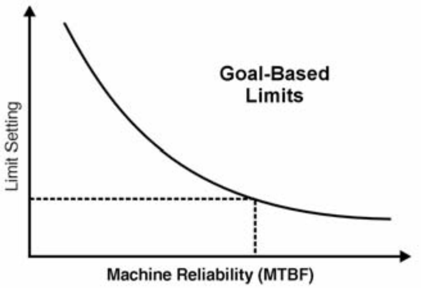


Figure 6-2 Goal-based Limits are Used to Reduce Stress (Contamination, for Example) on the Oil and Machine to Extend Service Life

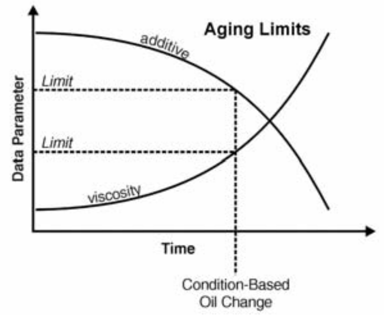
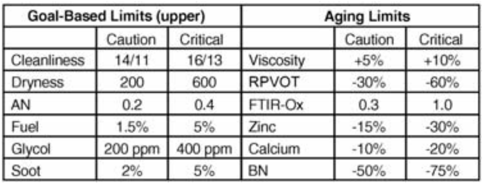


Figure 6-3 Aging Limits Alert Users to the Approaching End of the Service Life of the Oil or Machine Component



Goal-Based Limits (upper)			Aging Limits		
	Caution	Critical		Caution	Critical
Cleanliness	14/11	16/13	Viscosity	+5%	+10%
Dryness	200	600	RPVOT	-30%	-60%
AN	0.2	0.4	FTIR-Ox	0.3	1.0
Fuel	1.5%	5%	Zinc	-15%	-30%
Glycol	200 ppm	400 ppm	Calcium	-10%	-20%
Soot	2%	5%	BN	-50%	-75%

Figure 6-4 Example Limits for Both Goal-based and Aging Parameters

Predictive Alarms – Predictive alarms signal the presence of abnormal machine conditions or the onset of wear and failure. They are aligned with the goals of predictive maintenance – i.e., the early detection of machine failure symptoms as opposed to failure root causes (proactive maintenance). In oil analysis, a properly set predictive alarm has many advantages over other predictive maintenance technologies and, as such, represents an excellent complement to vibration analysis, thermography, etc. Within the predictive domain, we utilize the following oil analysis alarming techniques.

- **Rate-of-Change Alarms** – Rate of change alarms are typically set to measure properties that are being progressively introduced into the oil, such as wear debris. The add rate (change) can be calculated per unit of time, hours, cycles, etc. For example, a 100 ppm increase in iron over a period of 100 operating hours could be stated as one ppm per hour of operation. When the parameter is plotted against time, the rate-of-change (add rate) equals the current slope of the curve (see Figure 6-5). Unlike level limits, rate-of-change limits ignore the absolute value of the data parameter, emphasizing instead the speed at which the level is changing. Rate-of-change limits are effectively applied to particle counting (unfiltered systems), elemental wear metals, ferrous density, AN and RPVOT. It also can be effectively applied to monitor abnormal degradation of additives with elemental, LSV and FTIR spectroscopy.

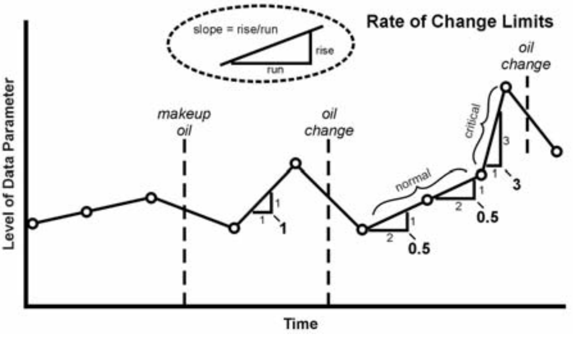
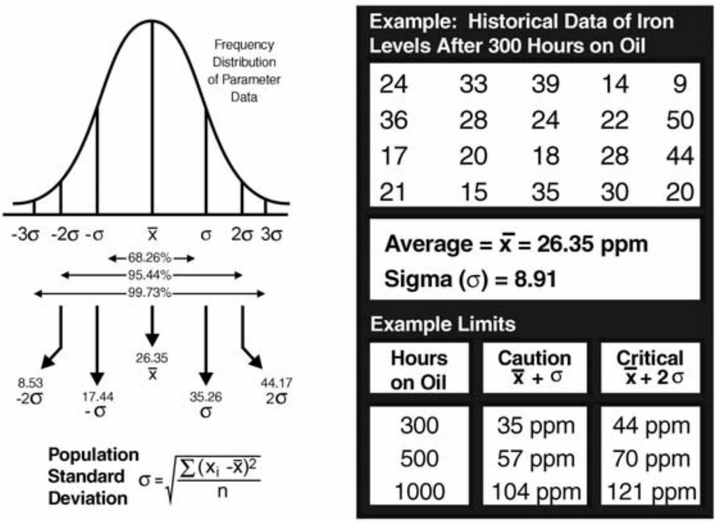


Figure 6-5 Trend-line Slope is a Visual Indication of Rate-of-change and Parameter Severity


Frequency Distribution of Parameter Data
-3σ
-2σ
-σ
$\bar{x}$
σ
2σ
3σ
68.26%
95.44%
99.73%
8.53 -2σ
17.44 -σ
26.35 $\bar{x}$
35.26 σ
44.17 2σ
Population Standard Deviation $\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n}}$

Example: Historical Data of Iron Levels After 300 Hours on Oil

24	33	39	14	9
36	28	24	22	50
17	20	18	28	44
21	15	35	30	20

Average = $\bar{x}$ = 26.35 ppm
Sigma (σ) = 8.91

Example Limits

Hours on Oil	Caution $\bar{x} + \sigma$	Critical $\bar{x} + 2\sigma$
300	35 ppm	44 ppm
500	57 ppm	70 ppm
1000	104 ppm	121 ppm

Figure 6-6 Statistical Analysis of Historic Data
to Assign Cautionary and Critical Limits

- **Statistical Alarms** – For many years, statistical alarms have been used effectively in oil analysis. The practice requires the availability of a sufficient quantity of machine- and application-specific historical data from which to draw meaningful conclusions. The statistical alarming approach is simple (see Figure 6-6). A population mean and associated standard deviation are generated from the available data. The data from a sample is compared to the mean of the population. If the value falls within one standard deviation of the mean, it is considered normal. If it falls outside of one standard deviation from the mean, but within two standard deviations, it is considered a caution. If the result exceeds two standard deviations, the value is considered in critical alarm as it is higher, or lower as the case may be, than 95% of the population. Should the value exceed three standard deviations, it is a critical situation indeed, as the value exceeds the 99th percentile of the population.

Figure 6-7 generally tabulates the applicability of different targeting and alarming techniques for specific oil analysis tests. It also identifies

	Goal-Based	Age-Based	Change Rate-Based	Statistics-Based
1. Particle Count	U	-	P	U
2. Viscosity				
a. 40°C	U, L	U, L	-	-
b. 100°C	U, L	U, L	-	-
3. AN	L	U	P, N	U, L
4. FTIR				
a. Ox/Nit/Sul	-	U	P	U
b. Phenol	-	L	N	L
c. ZDDP	-	L	N	L
d. Fuel Dil/Soot	-	U	P	U
e. Water	U	-	P	P
5. Ferrous Density	-	-	P	U
6. Analytical Ferrography	-	-	-	-
7. RPVOT	-	L	N	L
8. Water by Crackle	U	-	-	-
9. Water by KF	U	-	P	U
10. Water Separability	-	L	-	-
11. Elemental Analysis				
a. Wear Metals	-	-	P	U
b. Contaminants	U	-	P	U
c. Additives	-	L	N, P	L, U

Legend:
U = Upper Limit
L = Lower Limit
P = Positive Slope
N = Negative Slope
Note: Where alarms are bi-polar, the first shown is the most important.

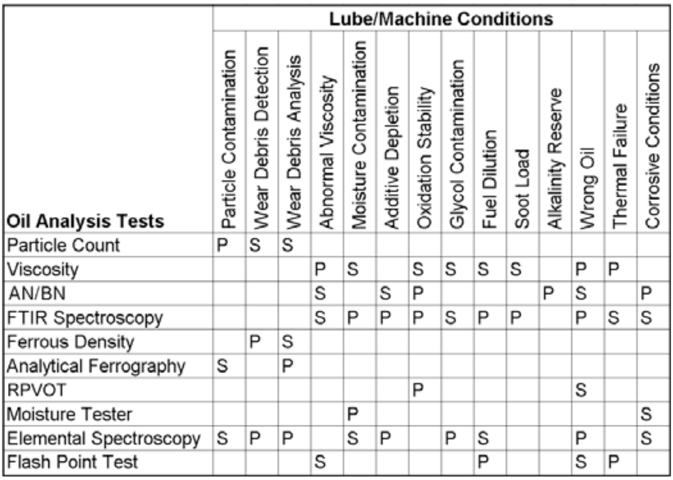
Figure 6-7 Table of Limit Types Applied to Data Parameters

whether the target or alarm is upper, lower or both. Statistical alarming methods are commonly applied to ferrous density, elemental metals and other predictive oil analysis measurements. While very useful in oil analysis, statistical data can result in false positives and negatives due to poor stratification of the data with respect to machine type, application and operating environment.

6.2 Interpreting and Applying Oil Analysis Results

Interpreting oil analysis data requires an understanding of the specific oil analysis tests, as described in Chapter 5, and an understanding about how these tests interrelate when oil and machine conditions change. Reference the table in Figure 6-8 during the discussion of the primary and secondary oil analysis indications for typical abnormal conditions.

It is important to note that this section serves only as an introduction to evaluative diagnostics for oil analysis. Many generalizations are made that don't hold true under all conditions.



	Lube/Machine Conditions													
Oil Analysis Tests	Particle Contamination	Wear Debris Detection	Wear Debris Analysis	Abnormal Viscosity	Moisture Contamination	Additive Depletion	Oxidation Stability	Glycol Contamination	Fuel Dilution	Soot Load	Alkalinity Reserve	Wrong Oil	Thermal Failure	Corrosive Conditions
Particle Count	P	S	S											
Viscosity				P	S		S	S	S	S		P	P	
AN/BN				S		S	P				P	S		P
FTIR Spectroscopy				S	P	P	P	S	P	P		P	S	S
Ferrous Density		P	S											
Analytical Ferrography	S		P											
RPVOT							P					S		
Moisture Tester					P									S
Elemental Spectroscopy	S	P	P		S	P		P	S			P		S
Flash Point Test				S					P			S	P	

P = Primary Indicator

S = Secondary Indicator

Figure 6-8 Table of Commonly Used Primary and Secondary (Confirming) Oil Analysis Indicators

6.2.1 Solid Particle Contamination. An alarm on particle contamination signals an increase in suspended particles due to occurrences such as the failure of a filter; ingestion of contaminants from the environment through seals or vents; contaminated new oil; or an increase in the internal generation of wear debris.

Primary Test:

- **Particle Count** – Use automatic particle counting (optical or pore blockage) or microscopic particle counting. Report ISO codes or counts about different sizes in microns, or both.

Alarming Strategy – Establish a predetermined cleanliness target based on reliability goals.

Secondary Tests:

- **Elemental Spectroscopy** – Often, when a particle count increases, the elemental levels of the particles present increase. For dirt-contaminated oil, silicon and aluminum increase as they are the primary constituents of the earth's crust. Likewise, wear metal elements may increase depending on the metallurgy of the failing components if the machine is experiencing abnormal wear. Note, however, that elemental spectroscopy produces frequent false negatives because the particles are often too large to be effectively measured by the instrument, as previously discussed.
- **Analytical Ferrography** – While expensive and time-consuming, depositing particles onto a slide or filter membrane disc and viewing them under a microscope will reveal an increase in particle count. Quantification of the particulate is limited with this technique.

Onsite Tests and Inspections:

- Patch test, onsite particle counting, used filter inspections, ferrous density tests, bottom sediment and water (BS&W) inspections

6.2.2 Wear Debris Detection. When machines are operating abnormally due to misalignment, imbalance, lubrication failure, contamination, corrosive conditions, etc., the machine sends messages into the oil in the form of wear debris. Oil analysis provides very early warning of this occurrence and increases the planning time and the number of options with which to correct the problem.

Primary Tests:

- **Ferrous Density** – Measuring an increase in the production of ferrous debris is a good indication of an abnormal situation because so many machine components are made from steel or iron. These tests are biased against non-magnetic wear debris generated from brass, bronze, aluminum, lead, tin and stainless steel surfaces.

- **Elemental Spectroscopy** – A rise in the level of elemental metals is an indication of the presence of an abnormal condition. And, by comparing results to component metallurgy records, the abnormal condition often can be qualified. Conventional elemental spectroscopy is particle-size limited and frequently produces false negative readings for wear debris until the particles are ground or corroded into very small pieces or dissolved.

Sampling Strategy – In close proximity to the wearing component or directly downstream of it

Secondary Test:

- **Particle Count** – Any wear that is generated will result in an increase in particle count. Particle count, however, reports no differentiation between ingested debris such as dirt and generated wear particles.

Onsite Tests and Inspections:

- **Magnetic Plug** – Inspect magnetic plugs for excessive debris accumulations.

- **Used Filter Debris** – Excessive amounts of wear debris on used filters should always be investigated.

6.2.3 Wear Debris Analysis. When an abnormal wearing condition is encountered, it must be analyzed to provide an indication of the nature, severity and root cause of the problem. This requires an investigation of the wear particles themselves along with a review of collateral information such as vibration analysis, operational information, lubrication analysis, etc.

Primary Tests:

- **Analytical Ferrography** – This microscopic technique provides an abundance of information about the wear debris and the wearing event. By evaluating particle size, dimension, shape and appearance, the analyst can often determine what wear mechanism generated the debris. By manipulating the particles with light, heat and chemicals, the metallurgy of the particles often can be defined.
- **Elemental Spectroscopy** – When machine component metallurgy is known, elemental spectroscopy proves invaluable for localizing wearing components. Because of the technique's particle size limitations, there is an occasional need for acid digestion of the particles to ensure accuracy.

Sampling Strategy – In close proximity to the wearing component or directly downstream of it

Secondary Tests:

- **Ferrous Density** – Trending an increase in the rate at which ferrous particles are generated provides important information about the severity of a failure event. Also, some ferrous density testers provide large and small ferrous particle differentiation. A rising "percent large particles" reading (from direct reading ferrography) suggests increased severity. These devices are biased toward magnetic particles.
- **Particle Count** – The rate at which particle count increases is indicative of the severity of the problem. Also, most particle counters sort the particles by size range. Increasing generation of large particles suggests high urgency. Particle counters lack the ability to differentiate particles by type (dirt or wear).
- **SEM/EDS** – Scanning electron microscopy can provide far greater detail of particle morphology than optical methods. Additionally,

the elemental composition of individual particles often can be determined.

- **XRF** – Often, it is beneficial to analyze filter debris, sludge samples and ferrous particles from magnetic plugs. XRF spectrometers are very well suited for these applications.

Onsite Tests and Inspections:

- **Magnetic Patch Method** – This involves using a magnet to selectively prepare a patch. One common way this is done is to prep the sample in a beaker first by diluting it with a solvent such as kerosene. Next, hold a strong magnet outside, tightly pressed against the bottom of the beaker. By swirling the diluted sample around, the ferromagnetic particles will pin down against the inside bottom of the beaker. The fluid, with the suspended non-ferrous particles, can then be poured off into the patch test funnel device (to microscopically observe a collection of non-ferrous particles). A crude estimation of ferrous density can be made by observing ferrous debris left behind in the bottom of the beaker. The final step is to remove the magnet, add more solvent to the beaker, and then pour the mixture of ferrous particles and solvent through the funnel to make a second patch showing only the ferrous particles.
- **Other Predictive Maintenance (PdM) Technologies** – There are many companion technologies that should be teamed with wear debris analysis for diagnosis and prognosis purposes. These include vibration analysis, infrared thermography and acoustic emissions.

6.2.4 Abnormal Viscosity. Viscosity can increase for a number of reasons. Oxidation, thermal failure, water/glycol contamination, soot loading and wrong oil are the most common reasons. Fuel or solvent dilution, VI improver (additive) shear-down, base oil shear-down and base oil cracking all reduce the viscosity.

Primary Tests:

- **Viscosity** – Viscosity is the "catch all" test for a number of abnormal lubricant or contaminant conditions. A change in viscosity is often an early indicator of other problems that need an expanded scope of analysis.

Sampling Strategy – From active fluid zones

Secondary Tests

- **AN** – If the increase in viscosity is associated with oxidative failure, the acid number (AN) will typically increase. AN sometimes increases or decreases when the wrong oil (and wrong viscosity) has been added to the sump because of the influence of the additive package on the AN.
- **FTIR Spectroscopy** – When viscosity changes because of thermal failure, oxidation, fuel/chemical dilution or glycol contamination, the FTIR spectrum tends to change at certain bands. If the wrong or mixed oil is being used, numerous spectral features will tend to change, as well.
- **Flash Point Test** – When the oil has been contaminated with fuel or solvents, the flash point will drop.
- Also: Depending on the nature of potential problem, additional tests include dielectric measurements, blotter spot testing, glycol reagent method, fuel dilution meter, membrane patch colorimetry and linear sweep voltammetry.

Onsite Tests and Inspections:

- Numerous field viscometers are available ranging in type, cost, accuracy and simplicity.
- Inspect for sludge, varnish, hot spots and oil color change.

6.2.5 Moisture Contamination. Moisture in all its forms brings nothing but trouble to the lubricant and machine. It rusts iron and steel surfaces, promotes corrosion on other metal surfaces, and over time can destroy the lubricant. Moisture can enter the oil from many places. The task of chasing the source down can be very complicated but still important to overall control.

Primary Tests:

- **Moisture Tester** – Water can be screened to about 500 ppm with the crackle test depending on the exact procedure employed and the type of oil. Quantification of the moisture content (if required) is best accomplished using the standard Karl Fischer titration procedure. Anti-wear, extreme-pressure and some rust-inhibiting additives may interfere with the accuracy of the test. Co-distillation Karl Fischer testing is the most accurate, as previously mentioned.

- **FTIR Spectroscopy** – FTIR serves as an effective screen for moisture above approximately 1,000 ppm for mineral oils, depending on the instrument's signal-to-noise ratio. FTIR also will signal the presence of glycol if leakage is from a cooler that uses glycol-based antifreeze. It also can provide useful information on additive depletion caused by the water contamination (water washing and/or hydrolysis).

Sampling Strategy – In close proximity to high-risk ingression points or directly downstream of them

Secondary Tests:

- **Viscosity** – When high levels of water contaminate oil, an emulsion is often formed. The viscosity, as measured by traditional viscometers, will increase under these conditions.

- **Elemental Spectroscopy** – Metals often accompany the ingested water. For instance, hard water brings calcium. Salt water brings sodium. Water and glycol bring sodium, boron and potassium, depending on the corrosion inhibitors used in the antifreeze. The source of the water often can be localized by examining the relative concentration of these trace metals.

- Also: Depending on the nature of potential problem, additional tests include dielectric measurements, blotter spot testing, glycol reagent method and linear sweep voltametry (LSV). LSV is a particularly effective technology to determine additive distress due to water contamination.

Onsite Tests and Inspections:

- Onsite moisture testers such as hot plate crackle test, calcium hydride moisture tester, dielectric measurements, etc.
- Clear and bright test (visual). Water forms emulsions in many types of lubricants that are visually apparent.

6.2.6 Additive Depletion. Additives are among the most difficult parameters to measure using oil analysis. The additives exist as organic, inorganic or organo-metallic compounds that improve base oil performance. Often, it is easier to assess the performance characteristic than the additive itself. Still, it is possible to estimate the remaining useful life of certain additives using conventional oil analysis techniques. New technologies have greatly expanded this capability.

Primary Tests:

- **Elemental Spectroscopy** – Many additives are organo-metallic compounds employing zinc, phosphorous, magnesium, calcium, silicon, etc. These levels can be effectively assessed using elemental spectroscopy. The technique has two primary limitations:
    1. Additives can be decomposed and their constituent elements transformed into other molecules with no visible change in elemental concentration. These are often referred to as dead additives. Their mass still exists in the oil, but they are no longer functional. For certain additives, a loss of elemental concentration of just 25% is enough to merit concern of the remaining 75% additive mass (that may be dead). Some additives lose mass by precipitation (drop-out), water washing, particle scrubbing, filtration, centrifugation, etc.
    2. Many additives have elements similar to wear metals and contaminants. For instance, dirt and some anti-foaming agents both appear on the oil analysis report as silicon.
- **FTIR Spectroscopy** – FTIR spectroscopy differs from elemental spectroscopy in that it evaluates the presence of molecules, not atoms. Therefore, it can effectively measure the presence of active

additive molecules, including organic molecules. It is limited by: (1) its poor ability to quantify additives in low concentrations and (2) interferences that might occur.

- **BN** – For engines, the oil's reserve alkalinity (detergent additive) is measured using the base number (BN) test. As BN declines, the oil's ability to counteract the ingress of combustion acids is weakened. A loss of BN signals the need for an oil change or makeup oil.
- Specialized Antioxidant Tests: RPVOT can estimate the condition of certain anti-oxidants. LSV and PDSC are also effective.
- Blotter Spot Test: The blotter spot test is extremely effective at assessing the condition of motor oil dispersancy.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **AN** – Industrial oils formulated with anti-wear, extreme-pressure and some anti-rust additives produce an elevated acid number originally in the formulated oil. As the additive depletes, the AN usually decreases. This decrease is typically followed by an increase once base oil oxidation begins. This is referred to as a switching trend.

Onsite Tests and Inspections:

- Field AN/BN kits
- Blotter spot testing

6.2.7 Oxidation Stability. Oxidation stability is an indication of the oil's lasting ability to resist oxidation (a common form of oil degradation). Heat and contamination over time will deteriorate an oil's resistance to oxidation. Some oil analysis tests measure the by-products of oxidation, while others attempt to measure the oil's ability to resist oxidation.

Primary Tests:

- **AN** – As an oil oxidizes, organic acids are produced. Measuring the concentration of these acids is a measure of oxidative damage that has occurred. The reliability of this measurement may be impaired by the presence of anti-wear, extreme-pressure and some rust-inhibiting additives. Additionally, not all acids found in oil relate to oxidation.

- **FTIR Spectroscopy** – During oxidation, the oil's base molecules (hydrocarbon) are turned into ketones, aldehydes, carboxylates and other transition molecules. These new molecules can be measured with FTIR spectroscopy. Likewise, FTIR provides some resolution in the measurement of certain oxidation-inhibiting additives, providing evidence of the oxidation stability.
- **RPVOT** – This test specifically measures the oil's ability to resist oxidation under accelerated and specific testing conditions. Other extremely useful tests include LSV and PDSC.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Viscosity** – Typically, as the oil oxidizes, its viscosity rises. As such, viscosity trending is not a good forecasting technique for oxidation stability but is rather a positive indication of the onset of oxidation.
- **Membrane Patch Colorimetry and Ultracentrifuge** – Oxidation produces by-products that change the color of the oil and form oxide insolubles. This can lead to varnish and sludge. These tests are particularly good at assessing this condition.

Onsite Tests and Inspections:

- Field AN kits; oxidation increases AN
- Oil inspection for oil color change and pungent odor
- Field viscometers of various types; oxidation increases viscosity
- Internal tank inspection for sludge and varnish; fouling of site glasses.

6.2.8 Glycol Contamination. Glycol (antifreeze) enters lubricating oils from the cooler. Leakage from corrosion, seal failure, cooler core damage and cavitation are the most common causes of glycol contamination. Glycol is extremely harmful to the lubricant (promotes oxidation and deposit formation), its additives (forms abrasive oil balls), filtration (plugs pores prematurely) and the engine (corrosion, wear, etc.). With so much at risk, the routine monitoring for trace glycol contamination in crankcase lubricants is a must.

Primary Tests:

- **Elemental Spectroscopy** – Most commercial antifreeze formulations include corrosion inhibitors that contain sodium, boron and/or potassium, among other elements. The inhibitors transfer into the oil with coolant (glycol) contamination. As such, they can be detected elementally by trending boron, sodium and/or potassium. The presence of these elements effectively serves as "markers" in detecting and quantifying glycol contamination. Because aftermarket antifreeze formulations contain different additive chemistry (some without organo-metallic additives), it is best to baseline the antifreeze being used for the inhibitor elements. This is done by sending a sample of the antifreeze to the lab in advance for elemental analysis. By knowing the relative concentrations of the additive elements in the antifreeze, it is easy to identify glycol contamination and to quantify its ingression in the oil. Lubricants with glycol greater than 50 ppm should be flagged.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Viscosity** – When a significant amount of glycol is present in used oil, there typically will be an increase in oil viscosity. Therefore, an increase in oil viscosity should be investigated as possible antifreeze contamination.

- **FTIR Spectroscopy** – Because it is so common to analyze crankcase lubricants using infrared spectroscopy (for soot, fuel dilution, oxidation, etc.), it is also practical to deploy its use in detecting glycol. Despite a number of possible interferences (water, antioxidants, oxidation products, etc.) and sensitivity to reference oil mismatch, FTIR can be an effective confirming test method.

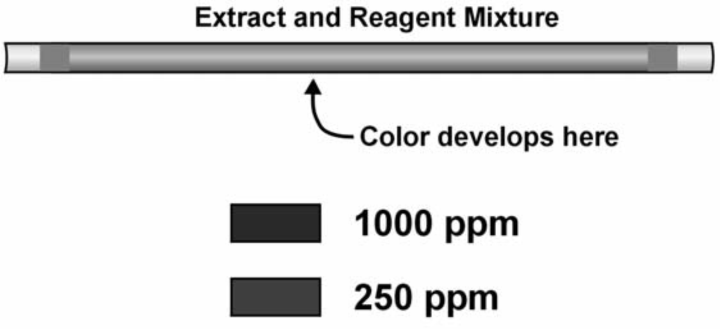


Figure 6-9 Schiff's Reagent Colorimetry Test for Glycol Contamination

Onsite Tests and Inspections:

- **Schiff's Reagent Method** – This is a colorimetric procedure used in the field and in the lab. If there is antifreeze in the oil, there will be a distinctive color produced by the chemical change of the glycol-contaminated oil when mixed with the Schiff's reagent (see Figure 6-9). Glycol often transforms rapidly into other chemicals after it contacts the oil. This condition frequently results in a false negative from this test.

- **Blotter Spot Test** – By placing a couple drops of oil on common blotter paper or card stock, you can obtain a qualitative assessment of glycol contamination. Permit the oil to wick into the blotter paper for at least a couple of hours. Glycol will often leave a pasty center on the blotter or a patch-like outward structure.

- Also: Field viscometers of various types; glycol raises viscosity.

6.2.9 Fuel Dilution. Fuel typically gets into the crankcase as an incomplete combustion by-product (blow-by) or by leakage. Either way, the influence of the fuel on lubrication can be substantial. For instance, just 10 percent fuel dilution can be enough to reduce an SAE 30 viscosity to an SAE 20. The reduced oil viscosity can alter critical oil film thickness in engine components. Additionally, the fuel dilutes additive concentrations. If excessive fuel levels are measured (above 3%), the source of the fuel must be determined and remedied.

Primary Tests:

- **Flash Point Testing** – When a lubricant is properly baselined, a sudden drop in flashpoint is a positive indication of fuel dilution. Typically, labs will flag an oil that exhibits a 20 to 30° C reduction in flash point. Rather than determining the actual flash point temperature, most labs set thresholds and run this as a pass/fail test.
- **FTIR Spectroscopy** – There are specific search areas in the infrared spectra that can be used to assess the presence of gasoline, diesel and jet fuels in lubricants. While the procedure is very sensitive to reference oil mismatch and certain interferences, FTIR is considered to be a valuable test for fuel dilution. Many FTIR spectrometers use calibration curves to estimate the percent fuel dilution and report these values.
- **Fuel Dilution Meter** – This instrument uses a headspace sampler to measure fuel vapor. This correlates well to fuel dilution using Henry's Law.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Viscosity** – Fuel contamination of crankcase oils sharply influences the blended viscosity. Fuel that enters the crankcase through the combustion chamber (blow-by) may consist of the heavier molecules only (i.e., reducing the resultant viscosity impact). However, raw fuel from leakage will sharply lower viscosity and oil film thickness.
- **Elemental Spectroscopy** – As previously mentioned, fuel dilution will dilute additive concentration. While a significant amount of fuel would be needed to produce a reduction in all additives measured by elemental analysis, it is still a common occurrence.

Onsite Tests and Inspections:

- Field viscometers of various types; fuel lowers viscosity
- Diesel fuel has a very distinct odor when mixed with motor oil

- Blotter spot testing has some sensitivity to fuel
- An elevation in oil level may be due to a fuel leak

6.2.10 Soot Load and Dispersancy. Soot enters crankcase oil from combustion blow-by. Excessive amounts occur when oil drains are overextended, air cleaners are plugged, rings/liners are worn and/or over-fueling conditions occur. As soot builds in the oil, the performance of the oil can degrade to eventually impair lubrication and result in the formation of sludge and deposits. Soot load and the quality of soot dispersancy (influenced by additives) impact the timing of a condition-based oil change for crankcase lubricants. Dispersancy is considered impaired when soot particles coagulate, forming carbon suspensions larger than 1 micron. Depending on the grade of oil and application, soot concentrations in the range of 2 to 5% are typically flagged as abnormal.

Primary Tests:

- **FTIR Spectroscopy** – Infrared provides a reliable, time-efficient test for soot load. It does not evaluate the quality of dispersancy, however. Because soot absorbs infrared energy across the full spectrum, its concentration is quantified by the resulting baseline shift (spectral shift). It is typically presented as percent soot or percent transmittance (for infrared).
- **Optical Soot Meters** – These can provide a quick and reliable determination of soot concentration.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Viscosity** – Viscosity generally will rise somewhat with increasing concentrations of soot. There is even a sharper impact on viscosity when dispersancy is lost. Occasionally, soot and fuel accumulate in crankcase oil concurrently. The resulting viscosity effect may be negligible (i.e., offsetting).

Onsite Tests and Inspections:

- **Blotter Spot Test** – By placing a couple drops of oil on common blotter paper or card stock, a qualitative assessment of soot load can be determined. The oil should be allowed to wick into the blotter paper for at least a couple of hours (see Figure 6-10). In addition to soot load, the appearance of well-defined annular structure (rings, halos, dark center spot, etc.) points to a loss of dispersancy. The blotter spot procedure for assessing dispersancy also is performed in oil analysis labs.
- Also: Field viscometers of various types; soot raises viscosity.

6.2.11 Alkalinity Reserve. Monitoring and controlling the reserve alkalinity of crankcase oils is key to any extended, condition-based oil drain strategy. Certain additives, like detergents, contribute to original alkalinity of the new oil. These additives essentially provide an antacid quality (by neutralizing) to the resulting formulation in combating acids that form from combustion and oxidation. Certain fuels (high in sulfur, for instance) and operating conditions (cold climates, short trips, etc.) contribute to a loss of alkalinity reserve. High blow-by from worn engines also can lead to corrosive conditions.

Primary Test:

- **BN** – This particular test has been performed for many years to assess alkalinity reserve by oil labs. The preferred procedure is ASTM D4739 or ASTM D5984-96. Crankcase oils are typically scheduled for change when BN drops to 50% of its original, new-oil level. BN results below two are considered critical (corrosive).

Onsite Tests and Inspections:

- Field BN test kits

6.2.12 Wrong Oil. One of the most common abnormal conditions detected by oil analysis is a wrong or non-complying oil. This can occur during an oil change, the addition of makeup oil or from additive top-treatments. In many applications, the use of a wrong oil can be as detrimental as a defective or contaminated oil. As such, the oil analysis test slate must have the ability to effectively recognize wrong or non-complying lubricants in use.

Primary Tests:

- **FTIR Spectroscopy** – The infrared spectrum is, in essence, a fingerprint of many properties of a formulated oil. If the base stock or additive package has changed sharply, this should be noticed by the laboratory spectroscopist.
- **Viscosity** – Often, the only meaningful difference when a wrong oil is applied is its viscosity.
- **Elemental Analysis** – The additive elements in a lubricant provide another way to fingerprint an oil at an atomic level. When elemental concentrations increase or decrease, this is a sudden tip-off that the oil has been altered.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Flash Point** – Oils of different viscosities, refining methods or base oil types (synthetic, natural esters, mineral, etc.) will tend to exhibit different flash points.
- **AN/BN** – Additives contribute considerably to BN and AN values in most oils. A sudden shift in AN or BN may be due to wrong or mixed oils.

Onsite Tests and Inspections:

- **Color/Odor** – A noticeable change in oil color or odor is always suspect but not a reliable indication of wrong oil. Occasionally, however, this is due to wrong, incompatible or mixed oils.
- Field viscometers of various types
- Dielectric measurements

6.2.13 Varnish Potential. Lubricants can thermally degrade for a variety of reasons, which can lead to sludge and surface deposits. Unlike oxidation, thermal failure can occur in new lubricants with healthy additive packages. However, many of the symptoms of oxidation also are symptoms of thermal degradation. One of the most common causes of thermal failure in hydraulic fluids and some lubricating oils relates to aeration (i.e., entrained air bubbles). These bubbles can become rapidly compressed in hydraulic pumps and in the squeeze zones of journal bearings. This results in extremely high localized temperatures (adiabatic compression), leading to sudden formation of carbon fines (see Figure 6-11). Hot surface carbonization is another form of thermal failure that causes carbon deposits. When an oil thermally degrades, problems associated with sludge, varnish, deposits, viscosity change and additive decomposition often will occur.

There is an assortment of other causes of varnish and sludge that aren't related to oxidation or thermal degradation. These include additive drop-out, additive degradation, chemical incompatibility and electrostatic discharge. Because of the many different causes and symptoms of varnish-producing conditions, the tests can be equally varied.

Primary Tests:

- **Ultracentrifuge** – Some labs utilize a sedimentation rating system that employs the use of ultracentrifugation. A small amount of sample is placed in a special plastic test tube centrifuged for 30 minutes at 20,000 rpm. This effectively extracts carbon insolubles, sludge and varnish precursors, driving them to the bottom of the tube. The density of the concentrated material is then compared to a visual sediment rating scale.

- **Membrane Patch Colorimetry** – This method has been getting plenty of attention in recent years for its ability to quantify varnish potential. Both insoluble and quasi-insoluble impurities are coagulated and deposited on a membrane for inspection using colorimetry.

- **Specialized Antioxidant Tests** – RPVOT can estimate the depletion of certain antioxidants. LSV and PDSC also are effective. Loss of oxidation stability is one of the most common precursors of varnish and sludge.

Sampling Strategy – From active fluid zones

Secondary Tests:

- **Viscosity** – Oxidation and thermal degradation can lead to either an increase or decrease in oil viscosity. Mild cases of thermal failure generally result in evaporative losses of the lighter fractions in the oil, leading to increased viscosity. Heat also is a primary factor in oxidation, which generally leads to increased viscosity. Extreme high temperatures (greater than 500° F) can crack the oil's hydrocarbon molecules, causing the oil to thin and the formation of dense carbon particles. If the extreme high temperature is due to aeration and adiabatic compression of air bubbles, it is possible that no change in viscosity will occur.

Onsite Tests and Inspections:

- **Blotter Spot Test** – By placing a couple drops of oil on common blotter paper or card stock, a qualitative assessment of carbon insol-

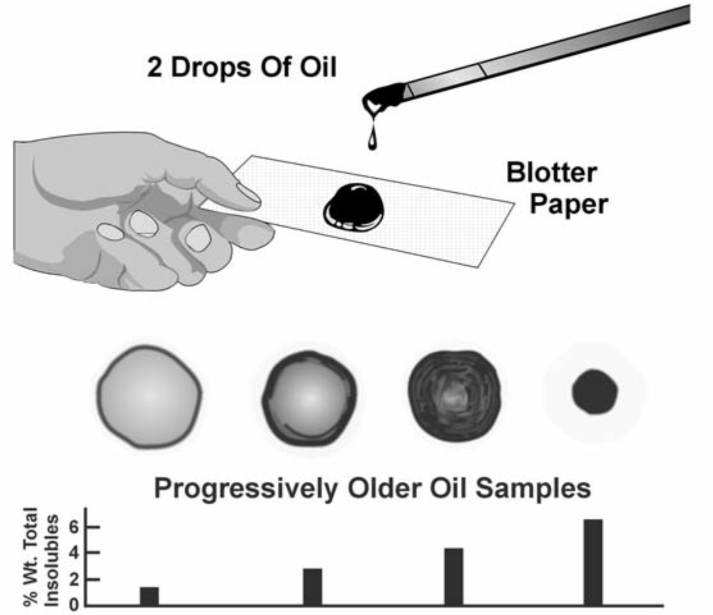


Figure 6-10 Blotter Spot Testing to Determine Soot Dispersancy

ubles can be determined. The oil should be allowed to wick into the blotter paper for at least a couple of hours. A dark spot or defined annular structure is a reliable indicator of carbon insolubles.

- **Color/Odor** – Varnish potential and thermal failure often is accompanied by a sharp darkening of the oil color. Sometimes, the odor will also change, ranging from a burnt food smell to no odor at all (the heat drives off all volatile, odor-bearing constituents).

6.2.14 Corrosive Conditions. A lubricant can become corrosive due to contamination of acids or the formation of acids through oxidative pathways. For instance, sulfuric and nitric acids can be produced from combustion blow-by products in engine crankcase oils. Phosphoric acids can come from additive breakdown and contamination. Other corrosive contaminants include hydrochloric and hydrofluoric acids. Regardless of the source or mode of acid formation, the risk is real and requires monitoring in most applications. Recognizing and correcting corrosive lubricating conditions can prevent very costly repairs and production losses.

Primary Tests:

- **AN/BN** – It is rare to have a serious corrosive condition without a significant change in AN in industrial lubricants and BN in crankcase oils. Therefore, these tests are typically selected to identify the increasing concentration of acidic compounds in lube oils and hydraulic fluids. Likewise, they provide trending capability for the depletion of certain corrosion inhibitors.

- **Moisture Tests** – When free and emulsified water contaminates an oil, suspended acids have much stronger corrosive potential.

Secondary Tests:

- **FTIR Spectroscopy** – As previously described, this test can detect acid products from oxidation as well as sulfation and nitration, which are associated with sulfuric acid and nitric acid.

- **Elemental Analysis** – Increasing wear metals are very often caused by corrosive wear, not mechanical wear.

Onsite Tests and Inspections:

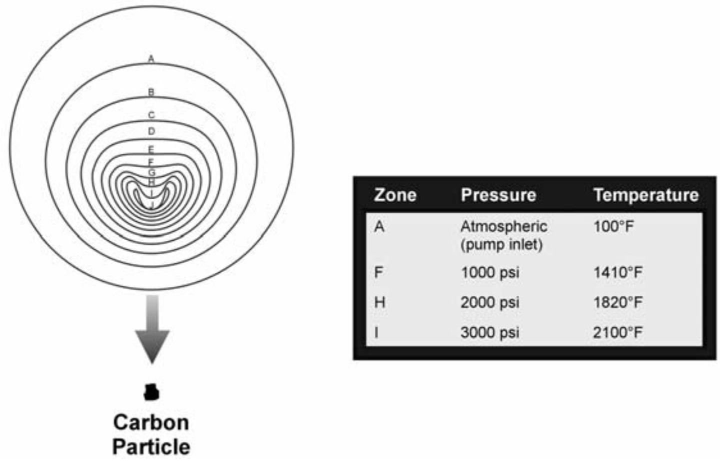
- Field AN/BN Tests
    - Field moisture tests such as the crackle test and calcium hydride testers; any cloudiness of the oil might be associated with water contamination
    - Internal inspection of machine surfaces for evidence of corrosion

6.3 Documenting and Reporting Oil Analysis Results

There are two specific reasons for which to document oil analysis results. First, proper documentation improves the technical quality of the oil analysis program, thus improving the effectiveness of maintenance and operations decisions. Also, good oil analysis reporting should facilitate financial justification of projects by trending performance to recognize productivity improvements resulting from effective lubrication management and/or oil analysis. A good oil analysis information management program has the following characteristics:

- Computer software that places the user in control of the data and maintains a permanent record of data and activities in-house.
- Supports onsite testing activities.
- Electronically downloads data generated by the laboratory.
- Is open architecture, not tying you to a specific laboratory or oil supplier.
- Provides effective routing and work management capabilities.
- Has user-definable report formatting capabilities.
- Integrates diagnostic notes to maintain a history of activities.
- Can be accessed by all those who require the data, with appropriate clearance assignment.
- Can work as a single-station program, or can be networked on a LAN or WAN system.

- Is easy to learn and use. The information should be in a format that is easy to understand and use to facilitate robust analysis. People tend to prefer graphic displays of data, in the form of graphs and plots, to plain numerical or text data. These tools allow the compression of large amounts of data, or derived values, to be viewed efficiently for analysis. Oil analysis data is typically reported and analyzed in a combination of data display types, which are described below:
    - **Multiple-parameter, Single-sample Data** – We frequently need to analyze multiple data parameters from a single sample to draw meaningful conclusions. An example is the elemental spectrum, where individual elements are defined on one axis of a table or bar chart and amplitude is defined on the other axis. Tables and bar charts are the most commonly used data display methods to report multiple-parameter, single-sample data.
    - **Single-parameter, Multiple-sample Data** – On other occasions, we need to look at the performance of a single parameter relative to time. This is a trend plot with time defined on the X axis and amplitude of the parameter of interest defined on the Y axis. This data display enables analysis with respect to absolute, relative or statistical limits, and supports rate-of-change-based alarming mechanisms.



Zone	Pressure	Temperature
A	Atmospheric (pump inlet)	100°F
F	1000 psi	1410°F
H	2000 psi	1820°F
I	3000 psi	2100°F

Figure 6-11 Adiabatic Thermal Failure Caused by Imploding Air Bubbles

- **X vs. Y Data Plots** – Occasionally, we wish to look at the performance of one variable relative to another to identify a visual trend or to calculate a coefficient of correlation. For example, ZDDP acts to improve the apparent lubricity of a fluid by reducing potential frictional forces. An examination of zinc levels vs. iron levels might indicate a correlation that would help us optimize fluid specification, fluid change intervals or fluid reconditioning schedules. The X vs. Y plot data display supports this sophisticated type of analysis.

6.4 Integrating Oil Analysis with Other Condition Monitoring Techniques

Oil analysis should not stand alone in the fight against machinery failure and unreliability. History has proved that there are numerous benefits gained from the use of complementary technologies for detecting abnormal machine conditions and for managing important failure root causes like misalignment and unbalance. Some of the most widely used complements to oil analysis include:

- Vibration analysis
- Thermography and thermometry
- Ultrasonic analysis
- Motor current evaluation

7. Guidelines for Selecting and Working with a Commercial Oil Analysis Laboratory

Selecting a commercial oil analysis lab is a process that involves many different considerations. No two labs are exactly the same and they vary in many significant ways. There currently are no accreditation services for used oil analysis laboratories, which means that users must go through the process of evaluating their options with limited guidance. This can be so complicated that, for most users, word-of-mouth and price tend to drive the selection decision.

It is usually best to begin with a detailed description of the task the lab is to perform. The more detailed and specific the work scope, the more satisfied users will be with the service. Leave as little to chance as possible. Several specific requirements should be spelled out. What follows are some of the issues to consider when selecting a lab:

- **Location** – Where should the lab be located? Many organizations prefer the lab to be geographically close to their plant so they can "run over" a sample if required. However, it may be just as efficient to express-ship samples across the country as sending them across town. There is some benefit to having the lab in the same time zone when questions arise. Still, for most users, the location of the lab is relatively low on the list of selection priorities.

- **Industry Orientation** – Many labs specialize in certain industries or even industry segments. For instance, there are labs that specialize in locomotives, aviation, trucking, off-road equipment, nuclear power plants, rotating equipment, hydraulic systems and the steel industry. Most labs advertise general, full-service capabilities, but a closer look might reveal a distinct area of specialty.

- **Turnaround Time** – A fault that is detected too late cannot be corrected in time to save the machine. It is, therefore, important that the lab commit to a reasonable turnaround time as requested by the customer. The lab's turnaround commitment often is reflected in the price charged. It is not unusual for a lab that guarantees 48-hour turnaround on routine samples to charge considerably more than a lab that offers no guarantee. In may be required to ask the lab for 24-hour turnaround for exception samples.

- **Test Capability** – There are a great many differences between labs in the area of capability. Some labs offer a wide array of ASTM testing capabilities, while others emphasize a narrow group of tests designed to satisfy the maintenance technologist concerned with the reliability of equipment and the health of lubricating oils. Refer to the recommended test slate previously described to ensure the lab can meet the minimum requirements.
- **Flexible Testing** – Many labs do not let customers design their own test bundles for machine types nor do they permit flexibility when it comes to exception testing. Flexibility from the lab may be required in order to develop appropriate test bundles for routine or exception testing.
- **Targets and Limits** – Certain labs permit customers to set limits for their equipment, while others do not. Requiring a customer to conform to a rigid set of limits may reduce the overall effectiveness of the oil analysis program.
- **Report Style** – The oil analysis report needs to conform to the needs of the customer. There should be both tabular and graphic presentation of oil analysis data. Likewise, the limits and targets set by the customer need to be visible on the report. Finally, the new oil baseline data must be shown next to the used oil data.
- **Quality Assurance** – Test accuracy is one of the most common complaints from customers about commercial oil analysis lab services. Presently, there is no independent control or verification of used oil analysis quality nor is there a licensing body for used oil analysis labs. Therefore, it is important to look at what the lab is doing to monitor itself. Here are some questions to ask:
    - Is the lab ISO 9002 certified?
    - Does it perform daily instrument calibration verification?

    - Are blind control samples processed by the lab to assess accuracy and performance?
    - Are control charts being maintained for each instrument showing test frequency and precision of calibration tests?
    - What quality assurance procedures have been put in place by the lab to manage its own quality?
    - Are lab technicians required to receive ongoing training to keep their skills current and to avoid "drift" into poor practice?

- **Electronic Data Service** – Modern oil analysis programs are generally paperless. It is far more efficient to spend time troubleshooting and examining the data of only machines that are non-conforming. Sophisticated oil analysis software programs are widely available that interface to commercial laboratory services.
- **Price** – This should be the last and least important consideration in selecting a lab. Oil analysis services are not a commodity, just as the services of a cardiologist should not be viewed as a commodity. The quality and effectiveness of oil analysis services will influence the overall effectiveness of the program and benefits received. The customer should expect to pay a fair price for timely and high-quality laboratory services.
- **Final Selection Process** – Once a work scope has been developed, the process described below is used to make the final selection:
    - Send out the request for bid to several labs that might meet requirements.
    - Interview (by phone) the labs that submit acceptable responses by phone.
    - Select the top two or three labs and ask them to submit references.
    - Select the top choice and an alternate.
    - Visit the top choice to see the operation and meet the people. If acceptable, award this lab the contract.

Appendix I – Glossary of Terms

Abrasion – A general wearing away of a surface by constant scratching, usually due to the presence of foreign matter such as dirt, grit or metallic particles in the lubricant. It also may cause a breakdown of the material (such as the tooth surfaces of gears). Lack of proper lubrication may result in abrasion.

Abrasive wear (or cutting wear) – Comes about when hard surface asperities or hard particles embed themselves into a soft surface and plough grooves into the opposing harder surface (e.g., a journal).

Absolute filtration rating – The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. This is an indication of the largest opening in the filter elements.

Absolute viscosity – A term used interchangeably with viscosity to distinguish it from either kinematic viscosity or commercial viscosity. Absolute viscosity is the ratio of shear stress to shear rate. It is a fluid's internal resistance to flow. The common unit of absolute viscosity is the poise. Absolute viscosity divided by fluid density equals kinematic viscosity. It is occasionally referred to as dynamic viscosity. Absolute viscosity and kinematic viscosity are expressed in fundamental units. Commercial viscosity such as Saybolt viscosity is expressed in arbitrary units of time (usually seconds).

Absorbent filter – A filter medium that holds contaminant by a mechanical means.

Absorption – The assimilation of one material into another; in petroleum refining, the use of an absorptive liquid can selectively remove components from a process stream.

AC Fine Test Dust (ACFTD) – A test contaminant used to assess both filters and the contaminant sensitivity of all types of tribological mechanisms.

Accumulator – A container in which fluid is stored under pressure as a source of fluid power.

Acid – In a restricted sense, any substance containing hydrogen in combination with a non-metal or non-metallic radical and is capable of producing hydrogen ions in solution.

Acid Number – The quantity of base, expressed in milligrams of potassium hydroxide, that is required to neutralize all acidic constituents present in 1 gram of sample. Formerly known as Total Acid Number.

Acidity – In lubricants, acidity denotes the presence of acid-type constituents whose concentration is usually defined in terms of acid number. The constituents vary in nature and may or may not markedly influence the behavior of the lubricant.

Additive – A compound that enhances some property of, or imparts some new property to, the base fluid. In some hydraulic fluid formulations, the additive volume may constitute as much as 20 percent of the final composition. The more important types of additives include antioxidants, anti-wear additives, corrosion inhibitors, viscosity index improvers and foam suppressants.

Additive stability – The ability of additives in the fluid to resist changes in their performance during storage or use.

Adhesion – The property of a lubricant that causes it to cling or adhere to a solid surface.

Adhesive wear – Often referred to as galling, scuffing, scoring or seizing. It happens when sliding surfaces contact one another, causing fragments to be pulled from one surface and to adhere to the other.

Adsorbent filter – A filter medium primarily intended to hold soluble and insoluble contaminants on its surface by molecular adhesion.

Adsorption – Adhesion of the molecules of gases, liquids or dissolved substances to a solid surface, resulting in a relatively high concentration of the molecules at the place of contact; e.g., the plating out of an anti-wear additive on metal surfaces.

Adsorptive filtration – The attraction to, and retention of particles in, a filter medium by electrostatic forces, or by molecular attraction between the particles and the medium.

Aeration – The state of air being suspended in a liquid such as a lubricant or hydraulic fluid.

AGMA – Abbreviation for "American Gear Manufacturers Association," an organization serving the gear industry.

Agglomeration – The potential of the system for particle attraction and adhesion.

Air, compressed – Air at any pressure greater than atmospheric pressure.

Air breather – A device permitting air movement between atmosphere and the component in/on which it is installed.

Alkali – Any substance having basic (as opposed to acidic) properties. In a restricted sense, it is applied to the hydroxides of ammonium, lithium, potassium and sodium. Alkaline materials in lubricating oils neutralize acids to prevent acidic and corrosive wear in internal combustion engines.

Analytical ferrography – The magnetic precipitation and subsequent analysis of wear debris from a fluid sample. This approach involves passing a volume of fluid over a chemically treated microscope slide which is supported over a magnetic field. Permanent magnets are arranged in such a way as to create a varying field strength over the length of the substrate. This varying strength causes wear debris to precipitate in a distribution with respect to size and mass over the ferrogram. Once rinsed and fixed to the substrate, this debris deposit serves as an excellent media for optical analysis of the composite wear particulates.

Anhydrous – Devoid of water.

Anti-foam agent – One of two types of additives used to reduce foaming in petroleum products: silicone oil to break up large surface bubbles, and various kinds of polymers that decrease the amount of small bubbles entrained in the oils.

Anti-friction bearing – A rolling-contact-type bearing in which the rotating or moving member is supported or guided by means of ball or roller elements. Anti-friction does not mean "without friction".

Anti-oxidants – These prolong the induction period of a base oil in the presence of oxidizing conditions and catalyst metals at elevated temperatures. The additive is consumed and degradation products increase not only with increasing and sustained temperature, but also with increases in mechanical agitation or turbulence and contamination (air, water, metallic particles and dust).

Anti-static additive – An additive that increases the conductivity of a hydrocarbon fuel to hasten the dissipation of electrostatic charges during high-speed dispensing, thereby reducing the fire/explosion hazard.

Anti-wear additives – These improve the service life of tribological elements operating in the boundary lubrication regime. Anti-wear compounds (for example, ZDDP and TCP) start decomposing at 90 to 100 degrees Celsius and even at a lower temperature if water (25 to 50 ppm) is present.

API engine service categories – Gasoline and diesel engine oil quality levels established jointly by API, SAE and ASTM, and sometimes called SAE or API/SAE categories; formerly called API engine service classifications.

API gravity – A gravity scale established by the American Petroleum Institute and in general use in the petroleum industry; the unit being called "the API degree." This unit is defined in terms of specific gravity as follows: API Gravity = 141.5/Specific Gravity @ 60°F/60° - 131.5

Ash – A measure of the amount of inorganic material in lubricating oil. Determined by burning the oil and weighing the residue. Results expressed as a percent by weight.

Asperities – Microscopic projections on metal surfaces resulting from normal surface-finishing processes. Interference between opposing asperities in sliding or rolling applications is a source of friction and can lead to metal welding and scoring. Ideally, the lubricating film between two moving surfaces should be thicker than the combined height of the opposing asperities.

ASTM – "American Society for Testing Materials", a society that develops standards for materials and test methods.

Atomic absorption spectroscopy – Measures the radiation absorbed by chemically unbound atoms by analyzing the transmitted energy relative to the incident energy at each frequency. The procedure consists of diluting the fluid sample with methyl isobutyl ketone (MIBK) and directly aspirating the solution. The actual process of atomization involves reducing the solution to a fine spray, dissolving it, and finally vaporizing it with a flame. The vaporization of the metal particles depends on their time in the flame, the flame temperature and the composition of the flame gas. The spectrum occurs because atoms in the vapor state can absorb radiation at certain well-defined characteristic wavelengths. The wavelength bands absorbed are very narrow and differ for each element. In addition, the absorption of radiant energy by electronic transitions from ground to excited state is essentially an absolute measure of the number of atoms in the flame and is, therefore, the concentration of the element in a sample.

Automatic transmission fluid (ATF) – Fluid for automatic, hydraulic transmissions in motor vehicles.

Axial-load bearing – A bearing in which the load acts in the direction of the axis of rotation.

Babbitt – A soft, white, non-ferrous alloy bearing material composed principally of copper, antimony, tin and lead.

Bactericide – Additive included in the formulations of water-mixed cutting fluids to inhibit the growth of bacteria promoted by the presence of water, thus preventing odors that can result from bacterial action.

Ball bearing – An anti-friction rolling-type bearing containing rolling elements in the form of balls.

Barrel – A unit of liquid volume of petroleum oils equal to 42 U.S. gallons or approximately 35 Imperial gallons.

Base – A material which neutralizes acids. An oil additive containing colloidally dispersed metal carbonate used to reduce corrosive wear.

Base Number (BN) – The quantity of acid, expressed in terms of potassium hydroxide, that is required to neutralize all basic constituents present in 1 gram of sample. Formerly known as Total Base Number.

Base stock – The base fluid, usually a refined petroleum fraction or a selected synthetic material, into which additives are blended to produce finished lubricants.

Bearing – A support or guide by means of which a moving part such as a shaft or axle is positioned with respect to the other parts of a mechanism.

Beta rating – The method of comparing filter performance based on efficiency. This is done using the Multi-Pass Test, which counts the number of particles of a given size before and after fluid passes through a filter.

Beta ratio (ß ratio) – The ratio of the number of particles greater than a given size in the influent fluid to the number of particles greater than the same size in the effluent fluid, under specified test conditions (see "Multi-Pass Test").

Bitumen – Also called asphalt or tar, bitumen is the brown or black viscous residue from the vacuum distillation of crude petroleum. It also occurs in nature as asphalt "lakes" and "tar sands." It consists of high molecular weight hydrocarbons and minor amounts of sulfur and nitrogen compounds.

Black oils – Lubricants containing asphaltic materials, which impart extra adhesiveness that are used for open gears and steel cables.

Blow-by – Passage of unburned fuel and combustion gases past the piston rings of internal combustion engines, resulting in fuel dilution and contamination of the crankcase oil.

Boundary lubrication – Form of lubrication between two rubbing surfaces without development of a full-fluid lubricating film. Boundary lubrication can be made more effective by including additives in the lubricating oil that provide a stronger oil film, thus preventing excessive friction and possible scoring. There are varying degrees of boundary lubrication depending on the severity of service. For mild conditions, oiliness agents may be used; by plating out on metal surfaces in a thin but durable film, oiliness agents prevent scoring under some conditions that are too severe for a straight mineral oil. Compounded oils, which are formulated with polar fatty oils, are sometimes used for this purpose. Anti-wear additives are commonly used in more severe boundary lubrication applications. The more severe cases of boundary lubrication are defined as extreme-pressure conditions; they are met with lubricants containing EP additives that prevent sliding surfaces from fusing together at high local temperatures and pressures.

Breakdown maintenance – Maintenance performed after a machine has failed to return it to an operating state.

Bridging – A condition of filter element loading in which contaminant spans the space between adjacent sections of a filter element, thus blocking a portion of the useful filtration.

Bright stock – A heavy residual lubricant stock with low pour point used in finished blends to provide good bearing film strength, prevent scuffing and reduce oil consumption. Usually identified by its viscosity, Saybolt Universal Seconds (SUS) at 210 degrees Fahrenheit or centistokes (cSt) at 100 degrees Celsius.

Brinelling – Permanent deformation of the bearing surfaces where the rollers (or balls) contact the races. Brinelling results from excessive load or impact on stationary bearings. It is a form of mechanical damage in which metal is displaced or upset without attrition.

British thermal unit (BTU) –The amount of heat required to raise the temperature of one pound of water 1 degree Fahrenheit.

Brookfield viscosity – Apparent viscosity in centipoises (cP) determined by a Brookfield viscometer, which measures the torque required to rotate a spindle at constant speed in oil of a given temperature. The basis for ASTM D2983, it is used for measuring low-temperature viscosity of lubricants.

Bubble point – The differential gas pressure at which the first steady stream of gas bubbles is emitted from a wetted filter element under specified test conditions.

Built-in dirt – Material passed into the effluent stream composed of foreign materials incorporated into the filter medium.

Bulk modulus (of elasticity) – A ratio of normal stress to a change in volume. A term used in determining the compressibility of a fluid. Data for petroleum products can be found in the International Critical Tables.

Burst pressure rating – The maximum specified inside-out differential pressure that can be applied to a filter element without outward structural or filter-medium failure.

Bushing – A short, externally threaded connector with a smaller-size internal thread.

Bypass filtration – A system of filtration in which only a portion of the total flow of a circulating fluid system passes through a filter at any instant or in which a filter having its own circulating pump operates in parallel to the main flow.

Bypass valve (relief valve) – A valve mechanism that assures system fluid flow when a preselected differential pressure across the filter element is exceeded; the valve allows all or part of the flow to bypass the filter element.

Cams – Eccentric shafts used in most internal combustion engines to open and close valves.

Capacity – The amount of contaminants that a filter will hold before an excessive pressure drop is caused. Most filters have bypass valves which open when a filter reaches its rated capacity.

Capillarity – A property of a solid-liquid system manifested by the tendency of the liquid in contact with the solid to rise above or fall below the level of the surrounding liquid; this phenomenon is seen in a small-bore (capillary) tube.

Carbon – A non-metallic element, No. 6 in the periodic table. Diamonds and graphite are pure forms of carbon. Carbon is a constituent of all organic compounds. It also occurs in combined form in many inorganic substances (i.e., carbon dioxide, limestone, etc.).

Carbon residue – Coked material remaining after an oil has been exposed to high temperatures under controlled conditions.

Carbonyl iron powder – A contaminant which consists of up to 99.5% pure iron spheres.

Case drain filter – A filter located in a line conducting fluid from a pump or motor housing to reservoir.

Catalyst – A substance which speeds a chemical action without undergoing a chemical change itself during the process. Now used in catalytic converters to control the amount of unburned hydrocarbons and carbon monoxide (CO) in automobile exhaust.

Catalytic converter – An integral part of vehicle emission control systems since 1975. Oxidizing converters remove hydrocarbons and carbon monoxide (CO) from exhaust gases, while reducing converters control nitrogen oxide (NOx) emissions. Both use catalysts of noble metals (platinum, palladium or rhodium) that can be "poisoned" by lead compounds in the fuel or lubricant.

Catastrophic failure – Sudden, unexpected failure of a machine, resulting in considerable cost and downtime.

Cavitation – Formation of an air or vapor pocket (or bubble) due to the lowering of pressure in a liquid, often as a result of a solid body (such as a propeller or piston) moving through the liquid; also, the pitting or wearing away of a solid surface as a result of the collapse of a vapor bubble. Cavitation can occur in a hydraulic system as a result of low fluid levels that draw air into the system, producing tiny bubbles that expand explosively at the pump outlet, causing metal erosion and eventual pump destruction.

Cavitation erosion – A material-damaging process which occurs as a result of vaporous cavitation. Cavitation refers to the occurrence or formation of gas- or vapor-filled pockets in flowing liquids due to the hydrodynamic generation of low pressure (below atmospheric pressure). This damage results from the hammering action when cavitation bubbles implode in the flow stream. Ultra-high pressures caused by the collapse of the vapor bubbles produce deformation, material failure and, finally, erosion of the surfaces.

Cellulose media – A filter material made from plant fibers. Because cellulose is a natural material, its fibers are rough in texture and vary in size and shape. Compared to synthetic media, these characteristics create a higher restriction to the flow of fluids.

Centipoise (**cp**) – A unit of absolute viscosity; 1 centipoise = 0.01 poise.

Centistoke (**cSt**) – A unit of kinematic viscosity; 1 centistoke = 0.01 stoke.

Centralized lubrication – A system of lubrication in which a metered amount of lubricant(s) for the bearing surfaces of a machine or group of machines is supplied from a central location.

Centrifugal separator – A separator that removes immiscible fluid and solid contaminants that have a different specific gravity than the fluid being purified. It operates by accelerating the fluid mechanically in a circular path and using the radial acceleration component to isolate these contaminants.

Chemical stability – The tendency of a substance or mixture to resist chemical change.

Chip control (**grit control, last-chance**) **filter** – A filter intended to prevent only large particles from entering a component immediately downstream.

Circulating lubrication – A system of lubrication in which the lubricant, after having passed through a bearing or group of bearings, is recirculated by means of a pump.

Cleanable – A filter element which, when loaded, can be restored by a suitable process to an acceptable percentage of its original dirt-holding capacity.

Clean room – A facility or enclosure in which air content and other conditions (such as temperature, humidity and pressure) are controlled and maintained at a specific level by special facilities and operating processes and by trained personnel.

Cleanliness level (CL) – A measure of relative freedom from contaminants.

Clearance bearing – A journal bearing in which the radius of the bearing surface is greater than the radius of the journal surface.

Cloud point – The temperature at which waxy crystals in an oil or fuel form a cloudy appearance.

Coalescer – A separator that divides a mixture or emulsion of two immiscible liquids using the interfacial tension between the two liquids and the difference in wetting of the two liquids on a particular porous medium.

Coefficient of friction – The number obtained by dividing the friction force resisting motion between two bodies by the normal force pressing the bodies together.

Cohesion – That property of a substance that causes it to resist being pulled apart by mechanical means.

Cold cranking simulator (CCS) – An intermediate shear rate viscometer that predicts the ability of an oil to permit a satisfactory cranking speed to be developed in a cold engine.

Collapse – An inward structural failure of a filter element which can occur due to abnormally high pressure drop (differential pressure) or resistance to flow.

Collapse pressure – The minimum differential pressure that an element is designed to withstand without permanent deformation.

Compound – (1) Chemically speaking, a distinct substance formed by the combination of two or more elements in definite proportions by weight and possessing physical and chemical properties different from those of the combining elements. (2) In petroleum processing, generally connotes fatty oils and similar materials foreign to petroleum added to lubricants to impart special properties.

Compounded oil – A petroleum oil to which has been added other chemical substances.

Compressibility – The change in volume of a unit volume of fluid when subjected to a unit change of pressure.

Compression ratio – In an internal combustion engine, the ratio of the volume of combustion space at bottom dead center to that at top dead center.

Compressor – A device which converts mechanical force and motion into pneumatic fluid power.

Consistency – The degree to which a semisolid material such as grease resists deformation (see ASTM D217). Sometimes used qualitatively to denote viscosity of liquids.

Contaminant – Any foreign or unwanted substance that can have a negative effect on system operation, life or reliability.

Contaminant (dirt, ACFTD) capacity – The weight of a specified artificial contaminant that must be added to the influent to produce a given differential pressure across a filter at specified conditions. Used as an indication of relative service life.

Contaminant failure – Any loss of performance due to the presence of contamination. Two basic types of contamination failure are: perceptible (gradual loss of efficiency or performance) and catastrophic (dramatic, unexpected failure).

Contaminant lock – A particle- or fiber-induced jam caused by solid contaminants.

Contamination control – A broad subject that applies to all types of material systems (including biological and engineering). It is concerned with planning, organizing, managing and implementing all activities required to determine, achieve and maintain a specified contamination level.

Coolant – A fluid used to remove heat (see Cutting fluid).

Copper strip corrosion – A qualitative measure of the tendency of a petroleum product to corrode pure copper.

Core – The internal duct and filter media support.

% Correlation – The percentage of peaks in the used oil infrared spectrum which match those in the reference oil. A sudden decrease in this value usually means that the oil was mixed with a different type.

Corrosion – The decay and loss of a metal due to a chemical reaction between the metal and its environment. It is a transformation process in which the metal passes from its elemental form to a combined (or compound) form.

Corrosion inhibitor – Additive for protecting lubricated metal surfaces against chemical attack by water or other contaminants. There are several types of corrosion inhibitors. Polar compounds wet the metal surface preferentially, protecting it with a film of oil. Other compounds may absorb water by incorporating it in a water-in-oil emulsion so that only the oil touches the metal surface. Another type of corrosion inhibitor combines chemically with the metal to present a non-reactive surface.

Coupling, quick disconnect – A coupling which can quickly join or separate lines.

Coupling – A straight connector for fluid lines.

Cracking – The process whereby large molecules are broken down by the application of heat and pressure to form smaller molecules.

Crown – The top of the piston in an internal combustion engine above the fire ring; is exposed to direct flame impingement.

Cryogenics – The branch of physics relating to the production and effects of very low temperatures.

Cutting fluid – Any fluid applied to a cutting tool to assist in the cutting operation by cooling, lubricating or other means.

Cycle – A single complete operation consisting of progressive phases starting and ending at the neutral position.

Cylinder – A device which converts fluid power into linear mechanical force and motion. It usually consists of a moveable element such as a piston and piston rod, plunger rod, plunger or ram, operating within a cylindrical bore.

Deaerator – A separator that removes air from the system fluid through the application of bubble dynamics.

Degas – Removing air from a liquid, usually by ultrasonic and/or vacuum methods.

Degradation – The progressive failure of a machine or lubricant.

Dehydrator – A separator that removes water from the system fluid.

Delamination wear – A complex wear process where a machine surface is peeled away or otherwise removed by forces of another surface acting on it in a sliding motion.

Demulsibility – The ability of a fluid that is insoluble in water to separate from water with which it may be mixed in the form of an emulsion.

Density – The mass of a unit volume of a substance. Its numerical value varies with the units used.

Deposits – Oil-insoluble materials that result from oxidation and decomposition of lube oil and contamination from external sources and engine blow-by. These can settle out on machine or engine parts. Examples are sludge, varnish, lacquer and carbon.

Depth filter – A filter medium that retains contaminants primarily within tortuous passages.

Desorption – Opposite of absorption or adsorption. In filtration, it relates to the downstream release of particles previously retained by the filter.

Detergent – In lubrication, either an additive or a compounded lubricant having the property of keeping insoluble matter in suspension, thus preventing its deposition, where it would be harmful. A detergent also may redisperse deposits already formed.

Dielectric strength – A measure of the ability of an insulating material to withstand electric stress (voltage) without failure. Fluids with high dielectric strength (usually expressed in volts or kilovolts) are good electrical insulators (ASTM D877) .

Differential pressure indicator – An indicator which signals the difference in pressure between any two points of a system or a component.

Dirt capacity (dust capacity, contaminant capacity) – The weight of a specified artificial contaminant which must be added to the influent to produce a given differential pressure across a filter at specified conditions. Used as an indication of relative service life.

Dispersant – In lubrication, a term usually used interchangeably with detergent. An additive, usually non-metallic ("ashless"), which keeps fine particles of insoluble materials in a homogeneous solution. Hence, particles are not permitted to settle out and accumulate.

Disposable – A filter element intended to be discarded and replaced after one service cycle.

Dissolved gases – Those gases that enter into solution with a fluid and are neither free nor entrained.

Distillation method (ASTM D95) – A method involving the distillation of a fluid sample in the presence of a solvent that is miscible in the sample but immiscible in water. The water distilled from the fluid is condensed and segregated in a specially designed receiving tube or tray graduated to directly indicate the volume of water distilled.

Drum – A container with a capacity of 55 U.S. gallons.

Duplex filter – An assembly of two filters with valving for selection of either or both filters.

Effluent – The fluid leaving a component.

Elastohydrodynamic lubrication – In rolling element bearings, the elastic deformation of the bearing (flattening) as it rolls, under load, in the bearing race. This momentary flattening improves the hydrodynamic lubrication properties by converting point or line contact to surface-to-surface contact.

Electrostatic separator – A separator that removes contaminant from dielectric fluids by applying an electrical charge to the contaminant that is then attracted to a collection device of different electrical charge.

Element (cartridge) – The porous device that performs the actual process of filtration.

Emission spectrometer – Works on the basis that atoms of metallic and other particular elements emit light at characteristic wavelengths when they are excited in a flame, arc or spark. Excited light is directed through an entrance slit in the spectrometer. This light penetrates the slit, falls on a grate, and is dispersed and reflected. The spectrometer is calibrated by a series of standard samples containing known amounts of the elements of interest. By exciting these standard samples, an analytical curve can be established which gives the relationship between the light intensity and its concentration in the fluid.

Emulsibility – The ability of a non-water-soluble fluid to form an emulsion with water.

Emulsifier – Additive that promotes the formation of a stable mixture, or emulsion, of oil and water. Common emulsifiers are: metallic soaps, certain animal and vegetable oils, and various polar compounds.

Emulsion – Intimate mixture of oil and water, generally of a milky or cloudy appearance. Emulsions may be of two types: oil-in-water (where water is the continuous phase) and water-in-oil (where water is the discontinuous phase).

End cap – A ported or closed cover for the end of a filter element.

Engine deposits – Hard or persistent accumulation of sludge, varnish and carbonaceous residues due to blow-by of unburned and partially burned fuel, or the partial breakdown of the crankcase lubricant. Water from the condensation of combustion products, carbon, residues from fuel or lubricating oil additives, dust and metal particles also contribute.

Environmental contaminant – All material and energy present in and around an operating system, such as dust, air moisture, chemicals and thermal energy.

Erosion – The progressive removal of a machine surface by cavitation or by particle impingement at high velocities.

Extreme-pressure (EP) additive – Lubricant additive that prevents sliding metal surfaces from seizing under conditions of extreme pressure. At the high local temperatures associated with metal-to-metal contact, an EP additive combines chemically with the metal to form a surface film that prevents the welding of opposing asperities and the consequent scoring that is destructive to sliding surfaces under high loads. Reactive compounds of sulfur, chlorine or phosphorus are used to form these inorganic films.

Extreme-pressure (EP) lubricants – Lubricants that impart to rubbing surfaces the ability to carry appreciably greater loads than would be possible with ordinary lubricants without excessive wear or damage.

Fabrication integrity point – The differential gas pressure at which the first stream of gas bubbles are emitted from a wetted filter element under standard test conditions.

False brinelling – False brinelling of needle roller bearings is actually a fretting corrosion of the surface since the rollers are the inside diameter (I.D.) of the bearing. Although its appearance is similar to that of brinelling, false brinelling is characterized by attrition of the steel, and the load on the bearing is less than that required to produce the resulting impression. It is the result of a combination of mechanical and chemical action that is not completely understood, and occurs in the presence of oxygen when a small relative motion or vibration is accompanied by some loading.

Fatigue chunks – Thick, three-dimensional particles exceeding 50 microns which indicate severe wear of gear teeth.

Fatigue platelets – Normal particles between 20 and 40 microns found in gearbox and rolling element bearing oil samples observed by analytical ferrography. A sudden increase in the size and quantity of these particles indicates excessive wear.

Fatigued – A structural failure of the filter medium due to flexing caused by cyclic differential pressure.

Ferrography – An analytical method of assessing machine health by quantifying and examining ferrous wear particles suspended in the lubricant or hydraulic fluid.

Film strength – Property of a lubricant that acts to prevent scuffing or scoring of metal parts.

Filter – Any device or porous substance used as a strainer for cleaning fluids by removing suspended matter.

Filter efficiency – Method of expressing a filter's ability to trap and retain contaminants of a given size.

Filter element – The porous device which performs the actual process of filtration.

Filter head – An end closure for the filter case or bowl that contains one or more ports.

Filter housing – A ported enclosure that directs the flow of fluid through the filter element.

Filter life test – A type of filter capacity test in which a clogging contaminant is added to the influent of a filter under specified test conditions to produce a given rise in pressure drop across the filter or until a specified reduction of flow is reached. Filter life may be expressed as test time required to reach terminal conditions at a specified contaminant addition rate.

Filter media, depth – Porous materials which primarily retain contaminants within a tortuous path, performing the actual process of filtration.

Filter media, surface – Porous materials which primarily retain contaminants on the influent face, performing the actual process of filtration.

Filtration (beta) ratio – The ratio of the number of particles greater than a given size in the influent fluid to the number of particles greater than the same size in the effluent fluid.

Filtration – The physical or mechanical process of separating insoluble particulate matter from a fluid, such as air or liquid, by passing the fluid through a filter medium that will not allow the particulates to pass through it.

Fire point (Clevelend Open Cup) – The temperature to which a combustible liquid must be heated so that the released vapor will burn continuously when ignited under specified conditions.

Fire-resistant fluid – Lubricant used especially in high-temperature or hazardous hydraulic applications. Three common types of fire-resistant fluids are: (1) water-petroleum oil emulsions, in which the water prevents burning of the petroleum constituent; (2) water-glycol fluids; and (3) non-aqueous fluids of low volatility, such as phosphate esters, silicones and halogenated hydrocarbon-type fluids.

Flash point (Cleveland Open Cup) – The temperature to which a combustible liquid must be heated to give off sufficient vapor to momentarily form a flammable mixture with air when a small flame is applied under specified conditions (ASTM D92).

Flow, laminar – A flow situation in which fluid moves in parallel lamina or layers.

Flow, turbulent – A flow situation in which the fluid particles move in a random manner.

Flow fatigue rating – The ability of a filter element to resist a structural failure of the filter medium due to flexing caused by cyclic differential pressure.

Flow rate – The volume, mass or weight of a fluid passing through any conductor per unit of time.

Flowmeter – A device that indicates either flow rate, total flow or a combination of both.

Fluid – A general classification including liquids and gases.

Fluid, fire resistant – A difficult-to-ignite fluid that shows little tendency to propagate flame.

Fluid compatibility – The suitability of filtration medium and seal materials for service with the fluid involved.

Fluid friction – Friction due to the viscosity of fluids.

Fluid opacity – Related to the ability of a fluid to pass light.

Fluid power – Energy transmitted and controlled through the use of a pressurized fluid.

Flushing – A fluid circulation process designed to remove contamination from the wetted surfaces of a fluid system.

Force-feed lubrication – A system of lubrication in which the lubricant is supplied to the bearing surface under pressure.

Fourier Transform Infrared (FTIR) spectroscopy – A test where infrared light absorption is used for assessing levels of soot, sulfates, oxidation, nitro-oxidation, glycol, fuel and water contaminants.

Fretting – Wear phenomenon taking place between two surfaces having oscillatory relative motion of small amplitude.

Fretting corrosion – Can take place when two metals are held in contact and subjected to repeated small sliding, relative motions. Other names for this type of corrosion include wear oxidation, friction oxidation, chafing and brinelling.

Friction – The resisting force encountered at the common boundary between two bodies when, under the action of an external force, one body moves or tends to move relative to the surface of the other.

Full-flow filter – A filter that, under specified conditions, filters all influent flow.

Full-flow filtration – A system of filtration in which the total flow of a circulating fluid system passes through a filter.

Full-fluid-film lubrication – Presence of a continuous lubricating film sufficient to completely separate two surfaces, as distinct from boundary lubrication. Full-fluid-film lubrication is normally hydrodynamic lubrication, whereby the oil adheres to the moving part and is drawn into the area between the sliding surfaces, where it forms a pressure (or hydrodynamic) wedge.

Gage – An instrument or device for measuring, indicating or comparing a physical characteristic.

Galling – A form of wear in which seizing or tearing of the gear or bearing surface occurs.

Gasohol – A blend of 10% anhydrous ethanol (ethyl alcohol) and 90% gasoline by volume. Used as a motor fuel.

Generated contaminant – Caused by a deterioration of critical wetted surfaces and materials or by a breakdown of the fluid itself.

Graphite – A crystalline form of carbon having a laminar structure, which is used as a lubricant. It may be of natural or synthetic origin.

Gravimetric analysis – A method of analysis whereby the dry weight of contaminant per unit volume of fluid can be measured, showing the degree of contamination in terms of milligrams of contaminant per liter of fluid.

Gravity – See Specific gravity, API gravity.

Grease – A lubricant composed of an oil(s) thickened with one or more soaps or other thickener to a semisolid or solid consistency.

Hardness – The resistance of a substance to surface abrasion.

Head – An end closure for the filter case or bowl which contains one or more ports.

Heat exchanger – A device which transfers heat through a conducting wall from one fluid to another.

Housing – A ported enclosure which directs the flow of fluid through the filter element.

Hydraulic fluid – Fluid serving as the power transmission medium in a hydraulic system. The most commonly used fluids are petroleum oils, synthetic lubricants, oil-water emulsions and water-glycol mixtures. The principal requirements of a premium hydraulic fluid are proper viscosity, high viscosity index, anti-wear protection (if needed), good oxidation stability, adequate pour point, good demulsibility, rust inhibition, resistance to foaming and compatibility with seal materials. Anti-wear oils are frequently used in compact, high-pressure and capacity pumps that require extra lubrication protection.

Hydraulic oil – An oil specially suited for use as either the specific gravity or the API gravity of a liquid.

Hydraulics – Engineering science pertaining to liquid pressure and flow.

Hydrocarbons – Compounds containing only carbon and hydrogen. Petroleum consists chiefly of hydrocarbons.

Hydrodynamic lubrication – A system of lubrication in which the shape and relative motion of the sliding surfaces causes the formation of a fluid film having sufficient pressure to separate the surfaces.

Hydrofinishing – A process for treating raw, extracted base stocks with hydrogen to saturate them for improved stability.

Hydrolysis – Breakdown process that occurs in anhydrous hydraulic fluids as a result of heat, water and metal catalysts (iron, steel, copper, etc.).

Hydrolytic stability – Ability of additives and certain synthetic lubricants to resist chemical decomposition (hydrolysis) in the presence of water.

Hydrometer – An instrument for determining either the specific gravity of a liquid or the API gravity.

Hydrostatic lubrication – A system of lubrication in which the lubricant is supplied under sufficient external pressure to separate the opposing surfaces by a fluid film.

Hypoid gear lubricant – A gear lubricant having extreme-pressure characteristics for use with a hypoid type of gear as in the differential of an automobile.

Image analyzer – A sophisticated microscopic system involving a microscope, a video camera, a dedicated computer and a viewing monitor.

Immiscible – Incapable of being mixed without separation of phases. Water and petroleum oil are immiscible under most conditions, although they can be made miscible with the addition of an emulsifier.

In-line filter – A filter assembly in which the inlet, outlet and filter element axes are in a straight line.

Indicator – A device which provides external evidence of sensed phenomena.

Indicator, pressure – An indicator that signals pressure conditions.

Indicator, differential pressure – An indicator that signals the difference in pressure between two points, typically between the upstream and downstream sides of a filter element.

Influent – The fluid entering a component.

Infrared spectroscopy – An analytical method using infrared absorption for assessing the properties of used oil and certain contaminants suspended therein (see FTIR).

Infrared spectra – A graph of infrared energy absorbed at various frequencies in the additive region of the infrared spectrum. The current sample, the reference oil and the previous samples are usually compared.

Ingested contaminants – Environmental contaminant that ingresses due to the action of the system or machine.

Ingression level – Particles added per unit of circulating fluid volume.

Inhibitor – Any substance that slows or prevents chemical reactions such as corrosion or oxidation.

Insolubles – Particles of carbon or agglomerates of carbon and other material. Indicates deposition or dispersant drop-out in an engine. Not serious in a compressor or gearbox unless there has been a rapid increase in these particles.

Intensifier – A device that converts low-pressure fluid power into higher-pressure fluid power.

Interfacial tension (IFT) – The energy per unit area present at the boundary of two immiscible liquids. It is usually expressed in dynes/centimeter (ASTM D971).

ISO Solid Contaminant Code (ISO 4406) – A code assigned on the basis of the number of particles per unit volume greater than 5 and 15 micrometers in size. Range numbers identify each increment in the particle population throughout the spectrum of levels.

ISO Standard 4021 – The accepted procedure for extracting samples from dynamic fluid lines.

ISO viscosity grade – A number indicating the nominal viscosity of an industrial fluid lubricant at 40° C (104° F) as defined by ASTM Standard Viscosity System for Industrial Fluid Lubricants D2422. Essentially identical to ISO Standard 3448.

Journal – That part of a shaft or axle that rotates or angularly oscillates in or against a bearing or about which a bearing rotates or angularly oscillates.

Journal bearing – A sliding type of bearing having either rotating or oscillatory motion and in conjunction with which a journal operates. In a full- or sleeve-type journal bearing, the bearing surface is 360 degrees in extent. In a partial bearing, the bearing surface is less than 360 degrees in extent (i.e., 150°, 120°, etc.).

Karl Fischer Volumetric Reagent Method (ASTM D1744-64) – The standard laboratory test to measure the water content of mineral base fluids. In this method, water reacts quantitatively with the Karl Fischer reagent. This reagent is a mixture of iodine, sulfur dioxide, pyridine and methanol. When excess iodine exists, electric current can pass between two platinum electrodes or plates. The water in the sample reacts with the iodine. When the water is no longer free to react with iodine, an excess of iodine depolarizes the electrodes, signaling the end of the test.

Kinematic viscosity – The time required for a fixed amount of an oil to flow through a capillary tube under the force of gravity. The unit of kinematic viscosity is the stoke or centistoke (1/100 of a stoke). Kinematic viscosity may be defined as the quotient of the absolute viscosity in centipoises divided by the specific gravity of a fluid, both at the same temperature (Centipoises ÷ Specific Gravity = Centistokes)

Lacquer – A deposit resulting from the oxidation and polymerization of fuels and lubricants when exposed to high temperatures. Similar to, but harder than, varnish.

Laminar particles – Particles generated in rolling element bearings which have been flattened out by a rolling contact.

Lead naphthenate – A lead soap of naphthenic acids, the latter occurring naturally in petroleum.

Light obscuration – The degree of light blockage as reflected in the transmitted light impinging on the photodiode.

Liquid – Any substance that flows readily or changes in response to the smallest influence. More generally, any substance in which the force required to produce a deformation depends on the rate of deformation rather than on the magnitude of the deformation.

Load-carrying capacity – Property of a lubricant to form a film on the lubricated surface which resists rupture under given load conditions. Expressed as the maximum load the lubricated system can support without failure or excessive wear.

Lubricant – Any substance interposed between two surfaces in relative motion for the purpose of reducing the friction and/or the wear between them.

Lubricity – Ability of an oil or grease to lubricate; also called film strength.

Magnet – A separator that uses a magnetic field to attract and hold ferromagnetic particles.

Magnetic filter – A filter element that, in addition to its filter medium, has a magnet or magnets incorporated into its structure to attract and hold ferromagnetic particles.

Magnetic plug – Strategically located in the flow stream to collect a representative sample of wear debris circulating in the system (for example, engine swarf, bearing flakes and fatigue chunks). The rate of buildup of wear debris reflects degradation of critical surfaces.

Manifold – A filter assembly containing multiple ports and integral relating components which services more than one fluid circuit.

Manifold filter – A filter in which the inlet and outlet port axes are at right angles, and the filter element axis is parallel to either port axis.

Media migration – Material passed into the effluent stream composed of the materials making up the filter medium.

Medium – The porous material that performs the actual process of filtration. The plural of this word is "media."

Metal oxides – Oxidized ferrous particles which are very old or have been recently produced by conditions of inadequate lubrication. Trending is important.

Micrometer (µm) – See Micron.

Micron – A unit of length; 1 micron = 39 millionths of an inch (.000039"). Contaminant size is usually described in microns. Relatively speaking, a grain of salt is about 60 microns, and the eye can see particles to approximately 40 microns. Many hydraulic filters are required to be efficient in capturing a substantial percentage of contaminant particles as small as 5 microns. A micron is also known as a micrometer, and exhibited as µm.

Microscope method – A method of particle counting which measures or sizes particles using an optical microscope.

Mineral oil – Oil derived from a mineral source, such as petroleum, as opposed to oils derived from plants and animals.

Miscible – Capable of being mixed in any concentration without separation of phases (e.g., water and ethyl alcohol are miscible).

Molybdenum disulfide (moly) – A solid lubricant and friction reducer, colloidally dispersed in some oils and greases.

Motor – A device which converts fluid power into mechanical force and motion. It usually provides rotary mechanical motion.

Multi-grade oil – An oil meeting the requirements of more than one SAE viscosity grade classification and may, therefore, be suitable for use over a wider temperature range than a single-grade oil.

Multi-pass or recirculation test – Filter performance tests in which the contaminated fluid is allowed to recirculate through the filter for the duration of the test. Contaminant is usually added to the test fluid during the test. The test is used to determine the beta ratio (q.v.) of an element.

Naphthenic – A type of petroleum fluid derived from naphthenic crude oil that contains a high proportion of closed-ring methylene groups.

Needle bearing – A type of bearing containing rolling elements that are relatively long compared to their diameter.

Newtonian fluid – A fluid with a constant viscosity at a given temperature regardless of the rate of shear. Single-grade oils are Newtonian fluids. Multi-grade oils are non-Newtonian fluids because viscosity varies with shear rate.

Nitration – Nitration products are formed during the fuel combustion process in internal combustion engines. Most nitration products are formed when an excess of oxygen is present. These products are highly acidic, form deposits in combustion areas and rapidly accelerate oxidation.

Nominal filtration rating – An arbitrary micrometer value indicated by a filter manufacturer. Due to a lack of reproducibility, this rating is deprecated.

Non-Newtonian fluid – Fluid, such as a grease or a polymer-containing oil (e.g., multi-grade oil), in which shear stress is not proportional to shear rate.

Non-woven medium – A filter medium composed of a mat of fibers.

Obliteration – A synergistic phenomenon of both particle silting and polar adhesion. When water and silt particles co-exist in a fluid containing long-chain molecules, the tendency for valves to undergo obliteration increases.

Oil – A greasy, unctuous liquid of vegetable, animal, mineral or synthetic origin.

Oiliness – Property of a lubricant that produces low friction under conditions of boundary lubrication. The lower the friction, the greater the oiliness.

Oil ring – A loose ring, the inner surface of which rides a shaft or journal and dips into a reservoir of lubricant from which it carries the lubricant to the top of a bearing by its rotation with the shaft.

Open bubble point (**boil point**) – The differential gas pressure at which gas bubbles are profusely emitted from the entire surface of a wetted filter element under specified test conditions.

Oxidation – Occurs when oxygen attacks petroleum fluids. The process is accelerated by heat, light, metal catalysts and the presence of water, acids or solid contaminants. It leads to increased viscosity and deposit formation.

Oxidation inhibitor – Substance added in small quantities to a petroleum product to increase its oxidation resistance, thereby lengthening its service or storage life; also called antioxidant. An oxidation inhibitor may work in one of these ways: (1) by combining with and modifying peroxides (initial oxidation products) to render them harmless; (2) by decomposing the peroxides; or (3) by rendering an oxidation catalyst inert.

Oxidation stability – Ability of a lubricant to resist natural degradation upon contact with oxygen.

Paper chromatography – A method which involves placing a drop of fluid on a permeable piece of paper and noting the development and nature of the halos, or rings, surrounding the drop through time. The roots of this test can be traced to the 1940s, when railroads used the "blotter spot" tests.

Paraffinic – A type of petroleum fluid derived from paraffinic crude oil and containing a high proportion of straight-chain-saturated hydrocarbons. Often susceptible to cold flow problems.

Particle count – The number of particles present greater than a particular micron size per unit volume of fluid; often stated as particles > 10 microns per milliliter.

Particle density – An important parameter in establishing an entrained particle's potential to impinge on control surfaces and cause erosion.

Particle erosion – Occurs when fluid-entrained particles moving at high velocity pass through orifices or impinge on metering surfaces or sharp angle turns.

Particle impingement erosion – A particulate wear process where high-velocity, fluid-entrained particles are directed at target surfaces.

Patch test – A method by which a specified volume of fluid is filtered through a membrane filter of known pore structure. All particulate matter in excess of an "average size", determined by the membrane characteristics, is retained on its surface. Thus, the membrane is discolored by an amount proportional to the particulate level of the fluid sample. Visually comparing the test filter with standard patches of known contamination levels determines acceptability for a given fluid.

Permeability – The relationship of flow per unit area to differential pressure across a filter medium.

pH – A measure of alkalinity or acidity in water and water-containing fluids. pH can be used to determine the corrosion-inhibiting characteristic in water-based fluids. Typically, pH greater than 8.0 is required to inhibit corrosion of iron and ferrous alloys in water-based fluids.

Pinion – The smaller of two mating or meshing gears; can be either the driving or the driven gear.

Pitting – A form of extremely localized attack characterized by holes in the metal. Pitting is one of the most destructive and insidious forms of corrosion. Depending on the environment and the material, a pit may take months or even years to become visible.

Pleated filter – A filter element whose medium consists of a series of uniform folds and has the geometric form of a cylinder, cone, disc, plate, etc.; synonymous with "convoluted" and "corrugated."

Pneumatics – Engineering science pertaining to gaseous pressure and flow.

Poise (absolute viscosity) – A measure of viscosity numerically equal to the force required to move a plane surface of one square centimeter per second when the surfaces are separated by a layer of fluid one centimeter in thickness. It is the ratio of the shearing stress to the shear rate of a fluid and is expressed in dyne seconds per square centimeter (dyne seconds ÷ cm^2); 1 centipoise equals .01 poise.

Polar compound – A chemical compound whose molecules exhibit electrically positive characteristics at one extremity and negative characteristics at the other. Polar compounds are used as additives in many petroleum products. Polarity gives certain molecules a strong affinity for solid surfaces. As lubricant additives (oiliness agents), such molecules plate out to form a tenacious, friction-reducing film. Some polar molecules are oil-soluble at one end and water-soluble at the other end. In lubricants, they act as emulsifiers, helping to form stable oil-water emulsions. Such lubricants are said to have good metal-wetting properties. Polar compounds with a strong attraction for solid contaminants act as detergents in engine oils by keeping contaminants finely dispersed.

Polishing (bore) – Excessive smoothing of the surface finish of the cylinder bore or cylinder liner in an engine to a mirror-like appearance, resulting in depreciation of ring sealing and oil consumption performance.

Polymerization – The chemical combination of similar-type molecules to form larger molecules.

Pore – A small channel or opening in a filter medium which allows passage of fluid.

Pore size distribution – The ratio of the number of effective holes of a given size to the total number of effective holes per unit area; expressed as a percent and as a function of hole size.

Porosity – The ratio of pore volume to total volume of a filter medium; expressed as a percent.

Positive crankcase ventilation (PCV) – System for removing blow-by gases from the crankcase and returning them through the carburetor intake manifold to the combustion chamber, where the recirculated hydrocarbons are burned. A PC valve controls the flow of gases from the crankcase to reduce hydrocarbon emissions.

Pour point – The lowest temperature at which an oil or distillate fuel is observed to flow when cooled under conditions prescribed by test method ASTM D97. The pour point is 3° C (5° F) above the temperature at which the oil in a test vessel shows no movement when the container is held horizontally for five seconds.

Pour point depressant – An additive which retards the adverse effects of wax crystallization and lowers the pour point.

Power unit – A combination of pump, pump drive, reservoir, controls and conditioning components which may be required for its application.

Predictive maintenance – A type of condition-based maintenance emphasizing early prediction of failure using non-destructive techniques such as vibration analysis, thermography and wear debris analysis.

Pressure – Force per unit area; usually expressed in pounds per square inch.

Pressure, absolute – The sum of atmospheric and gage pressures.

Pressure, atmospheric – Pressure exerted by the atmosphere at any specific location. (Sea level pressure is approximately 14.7 pounds per square inch absolute.)

Pressure, back – The pressure encountered on the return side of a system.

Pressure, cracking – The pressure at which a pressure-operated valve begins to pass fluid.

Pressure, rated – The qualified operating pressure which is recommended for a component or a system by the manufacturer.

Pressure, system – The pressure which overcomes the total resistances in a system. It includes all losses as well as useful work.

Pressure drop – Resistance to flow created by the element (media) in a filter. Defined as the difference in pressure upstream (inlet side of the filter) and downstream (outlet side of the filter).

Pressure gage – Pressure differential above or below atmospheric pressure.

Pressure line filter – A filter located in a line conducting working fluid to a working device or devices.

Preventive maintenance – Maintenance performed according to a fixed schedule involving the routine repair and replacement of machine parts and components.

Proactive maintenance – A type of condition-based maintenance emphasizing the routine detection and correction of root cause conditions that would otherwise lead to failure. Such root causes as high lubricant contaminant, alignment and balance are among the most critical.

psia – Pounds per square inch absolute (psig + 14.696).

psid – Pounds per square inch differential.

psig – Pounds per square inch gauge (psia - 14.696).

Pump – A device that converts mechanical force and motion into hydraulic fluid power.

Pumpability – The low-temperature, low-shear stress/shear rate viscosity characteristics of an oil that permit satisfactory flow to and from the engine oil pump and subsequent lubrication of moving components.

Pump, fixed displacement – A pump in which the displacement per cycle cannot be varied.

Pump, variable displacement – A pump in which the displacement per cycle can be varied.

Rate of shear – The difference between the velocities along the parallel faces of a fluid element divided by the distance between the faces.

Reducer – A connector having a smaller line size at one end than the other.

Refraction – The change of direction or speed of light as it passes from one medium to another.

Re-refining – A process of reclaiming used lubricant oils and restoring them to a condition similar to that of virgin stocks by filtration, clay adsorption or more elaborate methods.

Reservoir – A container for storage of liquid in a fluid power system.

Reservoir (sump) filter – A filter installed in a reservoir in series with a suction or return line.

Residual dirt capacity – The dirt capacity remaining in a service-loaded filter element after use, but before cleaning, measured under the same conditions as the dirt capacity of a new filter element.

Return line – A location in a line conducting fluid from working device to reservoir.

Return line filtration – Filters located upstream of the reservoir but after fluid has passed through the system's output components (cylinders, motors, etc.).

Ring lubrication – A system of lubrication in which the lubricant is supplied to the bearing by an oil ring.

Rings – Circular metallic elements that ride in the grooves of a piston and provide compression sealing during combustion; also used to spread oil for lubrication.

Ring sticking – Freezing of a piston ring in its groove in a piston engine or reciprocating compressor due to heavy deposits in the piston ring zone.

Roll-off cleanliness – The fluid system contamination level at the time of release from an assembly or overhaul line. Fluid system life can be shortened significantly by full-load operation under a high fluid contamination condition for just a few hours. Contaminant implanted and generated during the break-in period can devastate critical components unless removed under controlled operating and high-performance filtering conditions.

Roller bearing – An anti-friction bearing comprising rolling elements in the form of rollers.

Rust prevention test (turbine oils) – A test for determining the ability of an oil to aid in preventing the rusting of ferrous parts in the presence of water.

Sample preparation – Fluid factors that can enhance the accuracy of particulate analysis. Such factors include particle dispersion, particle settling and sample dilution.

Saturation level – The amount of water that can dissolve in a fluid.

Saybolt Universal Viscosity (SUV) or Saybolt Universal Seconds (SUS) – The time in seconds required for 60 cubic centimeters of a fluid to flow through the orifice of the Standard Saybolt Universal Viscometer at a given temperature under specified conditions (ASTM D88).

Scuffing – Abnormal engine wear due to localized welding and fracture. It can be prevented through the use of anti-wear, extreme-pressure and friction-modifier additives.

Scuffing particles – Large twisted and discolored metallic particles resulting from adhesive wear due to complete lubricant film breakdown.

Semisolid – Any substance having the attributes of both a solid and a liquid. Similar to a semiliquid but more closely related to a solid than a liquid. More generally, any substance in which the force required to produce a deformation depends both on the magnitude and on the rate of the deformation.

Shear rate – The rate at which adjacent layers of fluid move with respect to each other; usually expressed as reciprocal seconds.

Shear stress – Frictional force overcome in sliding one "layer" of fluid along another, as in any fluid flow. The shear stress of a petroleum oil or other Newtonian fluid at a given temperature varies directly with shear rate (velocity). The ratio between shear stress and shear rate is constant. This ratio is termed viscosity of a Newtonian fluid; increased shear stress is a function of rate of shear. In a non-Newtonian fluid – such as a grease or a polymer-containing oil (e.g., multi-grade oil) – shear stress is not proportional to the rate of shear. A non-Newtonian fluid may be said to have an apparent viscosity, a viscosity that holds only for the shear rate (and temperature) at which the viscosity is determined.

Silt – Contaminant particles 5 microns in size and smaller.

Silting – A failure generally associated with a valve; movements are restricted due to small particles that have wedged in between critical clearances (e.g., the spool and bore).

Single-pass test – Filter performance tests in which contaminant which passes through a test filter is not allowed to recirculate back to the test filter.

Sintered medium – A metallic or non-metallic filter medium processed to cause diffusion bonds at all contacting points.

Sleeve bearing – A journal bearing (usually a full journal bearing).

Sludge – Insoluble material formed as a result either of deterioration reactions in an oil or of contamination of an oil, or both.

Solid – Any substance having a definite shape which it does not readily relinquish. More generally, any substance in which the force required to produce a deformation depends on the magnitude of the deformation rather than on the rate of deformation.

Solvency – The ability of a fluid to dissolve inorganic materials and polymers; a function of aromaticity.

Specific gravity (liquid) – The ratio of the weight of a given volume of liquid to the weight of an equal volume of water.

Specific gravity – The ratio of the weight of a given volume of material to the weight of an equal volume of water.

Spectrometric analysis – This determines the concentration of elements represented in the entrained fluid sample; this is typically performed through emission spectroscopy.

Spectrometric Oil Analysis Program (SOAP) – Procedures for extracting fluid samples from operating systems and analyzing them spectrometrically for the presence of key elements.

Spin-on filter – A throw-away-type bowl and element assembly that mates with a permanently installed head.

Spindle oil – A light-bodied oil used principally for lubricating textile spindles and for light, high-speed machinery.

Splash lubrication – A system of lubrication in which parts of a mechanism dip into and splash the lubricant onto themselves and/or other parts of the mechanism.

Static friction – The force just sufficient to initiate relative motion between two bodies under load. The value of the static friction at the instant relative motion begins is termed breakaway friction.

Stoke (St) – The kinematic measurement of a fluid's resistance to flow defined by the ratio of the fluid's dynamic viscosity to its density.

Strainer – A coarse filter element (pore size over approximately 40 microns).

Suction filter – A pump intake-line filter in which the fluid is below atmospheric pressure.

Sulfated ash – The ash content of fresh, compounded lubricating oil as determined by ASTM D874. Indicates the level of metallic additives in the oil.

Sulfurized oil – Oil to which sulfur or sulfur compounds have been added.

Surface fatigue wear – The formation of surface or subsurface cracks and fatigue crack propagation. It results from cyclic loading of a surface.

Surface filtration – Filtration which primarily retains contaminant on the influent surface.

Surface tension – The contractile surface force of a liquid by which it tends to assume a spherical form and to present the least possible surface. It is expressed in dynes per centimeter or ergs per cubic centimeter.

Surfactant – Surface-active agent that reduces interfacial tension of a liquid. A surfactant used in a petroleum oil may increase the oil's affinity for metals and other materials.

Surge – A momentary rise of pressure in a circuit.

Swarf – The cuttings and grinding fines that result from metalworking operations.

Switch, pressure – An electric switch operated by fluid pressure.

Synthetic lubricant – A lubricant produced by chemical synthesis rather than by extraction or refinement of petroleum to produce a compound with planned and predictable properties.

Synthetic hydrocarbon – An oil molecule with superior oxidation quality tailored primarily out of paraffinic materials.

Thermography – The use of infrared thermography whereby temperatures of a wide variety of targets can be measured remotely and without contact. This is accomplished by measuring the infrared energy radiating from the surface of the target and converting this measurement to an equivalent surface temperature.

Thermal conductivity – The measure of the ability of a solid or liquid to transfer heat.

Thermal stability – The ability of a fuel or lubricant to resist oxidation under high-temperature operating conditions.

Thin film lubrication – A condition of lubrication in which the film thickness of the lubricant is such that the friction between the surfaces is determined by the properties of the surfaces as well as by the viscosity of the lubricant.

Thixotropy – Property of a lubricating grease which is manifested by a softening in consistency as a result of shearing followed by a hardening in consistency starting immediately after the shearing is stopped.

Three-body abrasion – A particulate wear process by which particles are pressed between two sliding surfaces.

Thrust bearing – An axial-load bearing.

Timken OK Load – The heaviest load that a test lubricant will sustain without scoring the test block in the Timken Test procedures – ASTM D2509 (greases) and D2782 (oils).

Tribology – The science and technology of interacting surfaces in relative motion, including the study of lubrication, friction and wear. Tribological wear is wear that occurs as a result of relative motion at the surface.

Turbidity – The degree of opacity of a fluid.

Turbulent flow sampler – A sampler that contains a flow path in which turbulence is induced in the main stream by abruptly changing the direction of the fluid.

Unloading – The release of contaminant that was initially captured by the filter medium.

Vacuum separator – A separator that utilizes sub-atmospheric pressure to remove certain gases and liquids from another liquid because of their difference in vapor pressure.

Valve, bypass – A valve whose primary function is to provide an alternate flow path.

Valve, directional control – A valve whose primary function is to direct or prevent flow through selected passages.

Valve, directional control, servo – A directional control valve which modulates flow or pressure as a function of its input signal.

Valve, flow control – A valve whose primary function is to control flow rate.

Valve, pressure control, relief – A pressure control valve whose primary function is to limit system pressure.

Valve, relief, differential pressure – A valve whose primary function is to limit differential pressure.

Valve – A device which controls fluid flow direction, pressure or flow rate.

Valve lifter – Sometimes called a "cam follower", it is a component in engine designs that uses a linkage system between a cam and the valve it operates. The lifter typically translates the rotational motion of the cam to a reciprocating linear motion in the linkage system.

Vapor pressure – Pressure of a confined vapor in equilibrium with its liquid at specified temperature; thus, a measure of a liquid's volatility.

Vapor Pressure, Reid (RVP) – Measure of the pressure of vapor accumulated above a sample of gasoline or other volatile fuel in a standard bomb at 100° F (37.8° C). Used to predict the vapor-locking tendencies of the fuel in a vehicle's fuel system. Controlled by law in some areas to limit air pollution from hydrocarbon evaporation while dispensing.

Varnish – When applied to lubrication, it is a thin, insoluble, nonwipeable film deposit occurring on interior parts, resulting from the oxidation and polymerization of fuels and lubricants. Can cause sticking and malfunction of close-clearance moving parts. It is similar to, but softer than, lacquer.

Viscometer or viscosimeter – An apparatus for determining the viscosity of a fluid.

Viscosity – Measurement of a fluid's resistance to flow. The common metric unit of absolute viscosity is the poise, which is defined as the force in dynes required to move a surface one square centimeter in area past a parallel surface at a speed of one centimeter per second, with the surfaces separated by a fluid film one centimeter thick. In addition to kinematic viscosity, there are other methods for determining viscosity, including Saybolt Universal Viscosity (SUV), Saybolt Furol viscosity, Engier viscosity and Redwood viscosity. Since viscosity varies inversely with temperature, its value is meaningless until the temperature at which it is determined is reported.

Viscosity, absolute – The ration of the shearing stress to the shear rate of a fluid. It is usually expressed in centipoise (cP).

Viscosity, kinematic – The absolute viscosity divided by the density of the fluid. It is usually expressed in centistokes (cSt).

Viscosity, SUS – Saybolt Universal Seconds is the time in seconds for 60 milliliters of oil to flow through a standard orifice at a given temperature (ASTM D8856).

Viscosity grade – Any of a number of systems which characterize lubricants according to viscosity for particular applications, such as industrial oils, gear oils, automotive engine oils, automotive gear oils and aircraft piston engine oils.

Viscosity index (VI) – A commonly used measure of a fluid's change of viscosity with temperature. The higher the viscosity index, the smaller the relative change in viscosity with temperature.

Viscosity index (VI) improvers – Additives that increase the viscosity of the fluid throughout its useful temperature range. Such additives are polymers that possess thickening power as a result of their high molecular weight. They are necessary for formulation of multigrade engine oils.

Viscosity modifier – Lubricant additive, usually a high-molecular-weight polymer, that reduces the tendency of an oil's viscosity to change with temperature.

Viscous – Possessing viscosity; this is frequently used to imply high viscosity.

Volatility – This property describes the degree and rate at which a liquid will vaporize under given conditions of temperature and pressure. When liquid stability changes, this property is often reduced in value.

Wear – The attrition or rubbing away of the surface of a material as a result of mechanical action.

Wicking – The vertical absorption of a liquid into a porous material by capillary forces.

Zinc dialkyldithiophosphate (ZDDP) – An anti-wear additive found in many types of hydraulic and lubricating fluids.

Abbreviations, Prefixes and Letter Symbols

amp – ampere

ARP – Aeronautical Recommended Practice

ASLE – American Society of Lubrication Engineers; changed now to Society of Tribologists and Lubrication Engineers (STLE)

ASME – American Society of Mechanical Engineers

ASTM – American Society for Testing Materials

ANSI – American National Standards Institute

atm – atmosphere

BTU – British thermal unit

C or cent. – Centigrade

cc – cubic centimeter

cm – centimeter

cfm – cubic feet per minute

gpm or GPM – gallons per minute

hp or HP – horsepower

HVI – High Viscosity Index, typically from 80 to 110 VI units

Hz – Hertz (cycles per second)

ISO – International Standards Organization (sets viscosity reference scales)

JIC – Joint Industry Conference

kg – kilograms

km – kilometer

kHz – kilohertz, or thousand Hertz (cycles per second)

log – logarithm (common)

LVI – Low Viscosity Index, typically below 40 VI units.

MIL – military

m or M – meter

µm – micron (micrometer)

NFPA – National Fluid Power Association

NEMA – National Electrical Manufacturers Association

NEC – National Electrical Code

NAS – National Aerospace Standard

NASA – National Aeronautics and Space Administration

P – pressure (as in psi)

ppm – parts per million (1/ppm = 0.000001), generally by weight (100 ppm = 0.01%; 10,000 ppm = 1%)

psi – pounds per square inch

psia – pounds per square inch absolute

Q – flow rate (as in GPM)

rpm – revolutions per minute

SAE – Society of Automotive Engineers (an organization serving the automotive industry)

SSU – Saybolt Universal Seconds (or SUS), a unit of measure used to indicate viscosity (e.g., SSU @ 100° F)

STLE – Society of Tribologists and Lubrication Engineers; formerly ASLE, American Society of Lubrication Engineers

t – time in seconds

T – temperature change, Fahrenheit

V – total volume (gals)

Prefixes – U.S. TERM

kilo – thousand

mega – million

centi – hundredth

milli – thousandth

micro – millionth

Cleanliness Definitions

Clean – 100 particles > 10 micron per milliliter

Superclean – 10 particles > 10 micron per milliliter

Ultraclean – 1 particle > 10 micron per milliliter

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